A Comparison of Methods for Estimating Groundwater-Surface Water Interactions in Braided Rivers

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By

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Abstract

Understanding how groundwater and surface water bodies interact is an important component of freshwater management. The direction and quantity of the flow between these two systems can vary in time and space, and these processes play various hydrological and ecological roles. The exchange of groundwater and surface water impacts water quantity, nutrient cycling, contaminant transport, and temperature regulation in surface water bodies for aquatic organisms. The interactions between these two systems can be difficult to measure and is often a poorly understood component of water budgets. Characterising these exchanges in gravel-bed braided rivers and their surrounding aquifers can be more difficult than in other environments due to their highly heterogeneous substrate; very permeable streambeds and subsurface material; dynamic geomorphology and flow levels; and difficulty installing direct measurement equipment into the coarse-gravel riverbeds.

In this study, mini-piezometers and vertical temperature probes were installed, and physicochemical analysis was carried out on the Hakatere/Ashburton River on the South Island of New Zealand. The methods were used to identify the direction of flow between groundwater and the river and quantify the rate of seepage through the streambed. Results from the methods were compared to assess their effectiveness for use in a braided river system. From a practical perspective, the purpose-built mini-piezometers and vertical temperature probes proved effective in this dynamic coarse-gravel environment. Results across the methods provided a complex picture of groundwater-surface water processes at the study sites, revealing areas of upwelling and downwelling through the streambed. The results reinforce the benefits of multi-method studies for investigating exchanges in groundwater and surface water, as they may better capture temporal and spatial variations in these flows, while providing robust study designs that allow for comparison of results across methods and redundancy in case of equipment or data collection failure.

Acknowledgements

While my name is on the cover of this thesis, this is by no means the work of one person. This research and the resulting thesis is a product of advice, funding, technical assistance and support from many people. I am grateful to all those I mention here for supporting me in this endeavour.

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Chapter 1. Introduction

Braided rivers are highly valued water resources for their economic, recreational and ecological values. However, they are complex and dynamic systems, which can make it difficult to manage them effectively. One aspect that complicates the understanding of braided rivers relates to groundwater and surface water interactions. Braided rivers are characterised by multiple meandering channels that deposit gravel bars and islands, which generally create a highly porous and interconnected environment for groundwater and surface water to mix.

There are various methods available for investigating groundwater-surface water exchange in rivers including environmental tracers, chemical analysis, flow gauging, groundwater well monitoring and modelling. There are advantages and disadvantages to each method and rarely is there a single "perfect" method for a study. Many researchers have successfully used a combination of methods for these types of investigations (e.g. Burbery & Ritson, 2010; Cey et al., 1998; Lee & Cherry, 1978). This study utilised a multi-method approach for identifying groundwater-surface water interaction in the Hakatere/Ashburton River on the South Island of New Zealand. The methods included mini-piezometers, vertical temperature probes, physicochemical sampling and flow gauging to locate areas of seepage through the streambed as well as quantify seepage rates. The results from the various methods were compared to assess their effectiveness in achieving the study's objectives.

1.1 Research aim & objectives

Aim: This research aims to assess the usefulness of several simple (i.e. inexpensive and easy to deploy) field methods for characterising groundwater-surface water interactions in the Hakatere/Ashburton River.

Objectives

1. Install mini-piezometers and vertical temperature probes in the river and its margins.

2. Carry out flow gauging in the South Branch of the Hakatere/Ashburton River to determine reaches that are gaining groundwater and those that are losing river flow to groundwater.

3. Use these methods to identify areas of groundwater-surface water connectivity and calculate rates of seepage through the streambed.

4. Carry out physical and chemical analysis of the water to enhance the understanding of water and nutrient sources at the study sites.

5. If necessary, refine the design of the techniques to make them more suitable for use in braided rivers.

6. Critically assess the usefulness of these tools for groundwater-surface water investigations in braided rivers.

Study implications

- Identify new methods for use in braided rivers using inexpensive and easy-to-install tools.
- Enhance the understanding of groundwater flow paths.
- Improve the knowledge base for the sustainable allocation of water in the Ashburton Zone.
- Potentially identify hotspots of contamination to the Hakatere/Ashburton River and surrounding shallow groundwater.

Chapter 2. Background

2.1 Groundwater-surface water interactions

Understanding the interactions between groundwater and surface water is becoming increasingly recognised as a crucial component of effective water resource management (Brodie et al., 2007; Woessner, 2000). Historically, groundwater and surface water systems have often been considered independently both in research and in the way they have been managed as resources (Kalbus et al., 2006). However, in the past few decades there has been a considerable increase in research focusing on groundwater and surface water interactions (Rosenberry & LaBaugh, 2008). There are various spatial and temporal scales at which groundwater and surface water interact (Kalbus et al., 2006; Lovett, 2015), and it is necessary to have a thorough understanding of these factors to accurately characterise the movement of water between these systems.

The interface between surface water and groundwater is an important transition zone of water and chemical mixing and is often characterised by low flow rates, permeable sediments and saturated conditions (Kalbus et al., 2006). Groundwater can exchange with a variety of surface water bodies such as lakes, wetlands and rivers. Groundwater can flow into surface water bodies and likewise, surface water bodies can recharge surrounding groundwater systems. The direction of exchange is a factor of hydraulic head (i.e. water moves from areas of higher elevation to lower), except in the case of disconnected systems where the surface water body and groundwater are separated by an unsaturated zone (Kalbus et al., 2006). Figure 2.1 illustrates how these various interactions can occur in rivers.

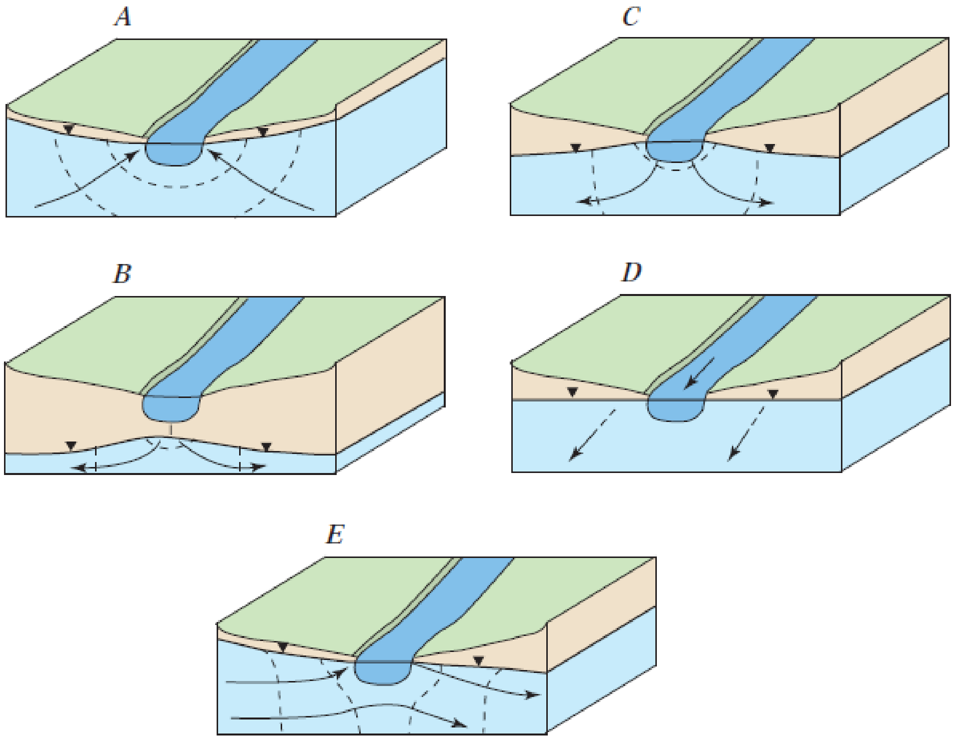


Figure 2.1.Groundwater and stream channel interactions classified as: A, gaining; B, disconnected losing; C, losing; D, zero exchange; and E, throughflow. The dashed lines are equipotential lines. Source: Woessner (1998).

In terms of water management, understanding groundwater-surface water interactions is critical for predicting contaminant transport and accurately quantifying sustainable surface water and groundwater allocations. As groundwater and surface water systems are interconnected, often the development or contamination of one system will affect the other. For example, pumping from groundwater wells hydraulically connected to a nearby river could cause a reduction in river flows. Or, in a location where nutrient-rich groundwater flows into rivers, this can be a source of contamination. Also, groundwater seepage into rivers often serves as a critical source of river baseflow during dry periods.

These interactions are also important to understand because of their significance to ecosystems in groundwater, surface water, and the hyporheic zone—the mixing zone between surface and sub-surface waters. The hyporheic zone is particularly rich in biogeochemical activity (Febria et al., 2011), and groundwater-surface water interactions have been increasingly recognised as an important aspect of freshwater ecology (Kilroy et al., 2004).

Among the questions that can be examined through groundwater-surface water investigations include the locations of groundwater discharge or recharge, as well as the rate of groundwater flux at specific locations or average values on a regional scale. These questions can be considered at various spatial and temporal scales (Lovett, 2015).

2.2 Groundwater-surface water exchange in braided rivers

Braided rivers are significant in terms of their unique ecosystems and as vital freshwater resources for a variety of uses. Globally, braided rivers are rare; they are mainly found in Canada, Alaska, the Himalayas, New Zealand, and the European and Japanese Alps (Tockner et al., 2006). Braided rivers are often strongly connected to groundwater systems due to their highly permeable streambeds, with many reaches along rivers gaining flow from groundwater or losing surface water to aquifers. There is an increasing recognition of the importance of understanding how groundwater and surface water interact for applications such as determining the rate and direction of contaminant flow, and identifying sustainable volumes of water that can be abstracted from aquifers and surface water bodies.

Braided rivers are a highly dynamic type of river with meandering channels, wide bars and variable flow levels. They generally occur in mountainous areas with a large sediment source (such as glacial outwash), high river discharge rates and a steep topographic gradient (Charlton, 2008). The high-energy environments in which they exist enable the rivers to carry large sediment loads. When these rivers reach their capacity to carry sediment, they form braids, which branch out and re-join, creating islands and shallow bars (Landcare Research New Zealand Limited, n.d.) (see Figure 2.2). Bars and islands are often referred to as distinct features, with bars existing at periods of low flow, while islands are generally more permanent features that may be vegetated (Charlton, 2008). Braided rivers can completely change their geometry over a few decades. They undergo expansion and contraction phases in which their channels widen or narrow, depending on sediment supply and river flows (Piégay et al., 2006). The wetted channels of the river can shift, abandoning channels and re-occupying old channels (Charlton, 2008). Relatively erodible streambanks, which allow for wide channels to form and meander, are a key characteristic of braided rivers. These types of rivers generally have gravel beds, but can be comprised of sand beds (e.g. the Brahmaputra-Jamuna River, which flows through India and Bangladesh). While this research has applications in all braided river environments, it focuses specifically on braided gravel-bed rivers.

Figure 2.2. An aerial photo of the Rakaia River on the South Island of New Zealand displaying a typical braided pattern. Source: Photograph by Lloyd Homer as cited in Scarsbrook and Pearson (2008).

The geomorphology of braided rivers is very dynamic—their bars frequently shift locations during flood events. Where they are not physically constrained, the width and position of the river channels often change. Braided rivers both erode and deposit sediment, and there is a continual dynamism between these two processes. The factors that create the conditions for these processes include the rate and amount of precipitation, as well as the gradient over which the river flows. Depending on factors such as flow rate, channel gradient, sediment load and channel stability, various types of river forms will occur such as braided, anastomosing or meandering (Figure 2.3). Some rivers, such as the Rangitata on the South Island of New Zealand, have alternating braided and meandering reaches. These types of rivers, which are close to these “thresholds” of form, may be more sensitive to fluctuations in sediment load or flow levels (Charlton, 2008).

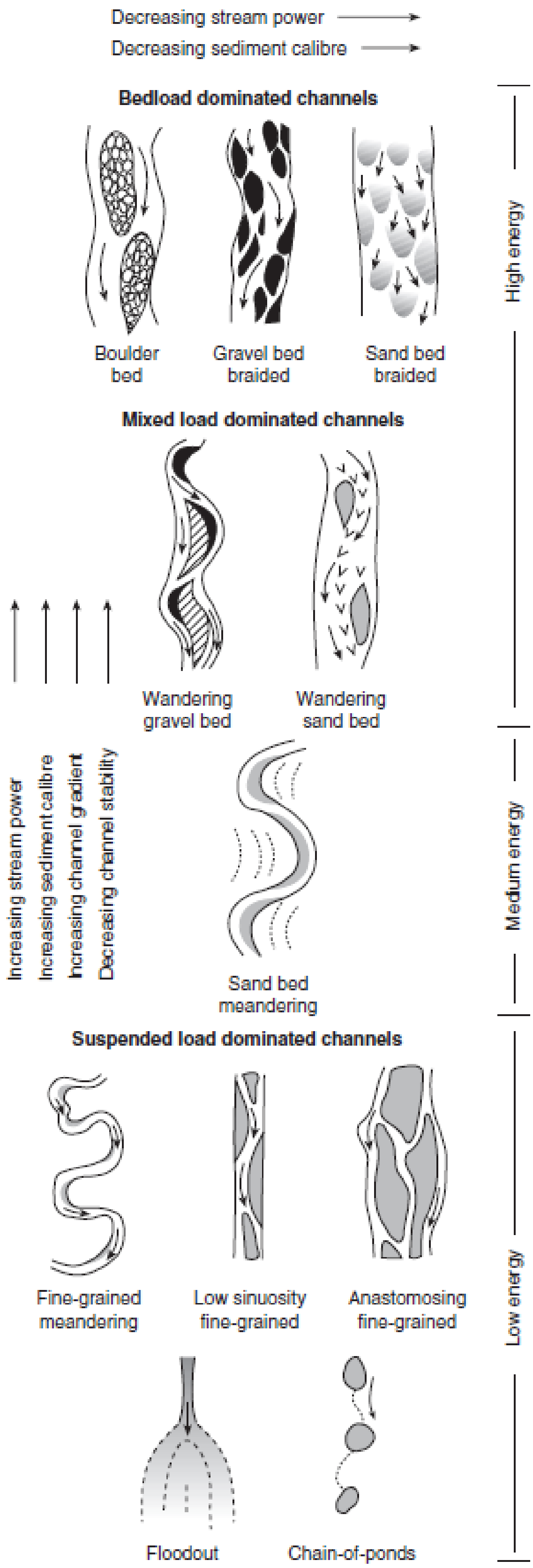


Figure 2.3. Types of river channels that form under varying conditions. Source: Charlton (2008).

Braided river deposits form important aquifers, and the nature of their deposition influences groundwater flow rates and direction. The complex depositional processes of braided rivers often create heterogeneous aquifers, with hydrogeological properties such as hydraulic conductivity and porosity varying throughout aquifers (Huggenberger & Regli, 2006). Also, a significant portion of sub-surface flow in aquifers formed by braided rivers can occur in open framework channels, which are essentially previous river flow channels that form preferential flow paths for groundwater because of their high hydraulic conductivity (Close et al., 2014; White, 2009). The complexity of these heterogeneous systems can make their management as freshwater resources challenging. For example, there is significant uncertainty surrounding rates of groundwater recharge from large braided rivers, which complicates the sustainable allocation of water extraction rights from surface water and groundwater sources (Close et al., 2014).

As with many other types of rivers, braided rivers face pressures from human activities. Their channels, streambeds and margins are often heavily altered by human activities such as gravel extraction, channel modifications and damming. This can influence river processes in many ways, including altering the rate of sedimentation or changing the flow regime, which may impact various uses of the rivers as well as riparian ecosystems (Piégay et al., 2006).

Braided rivers have significant ecological value, providing habitat for many plant and animal species specifically adapted to survive in the dynamic, nutrient-poor environment of the rivers' gravel bars and their margins. In New Zealand, the rivers contain some of the last remaining native habitat on the heavily modified Canterbury Plains of the South Island, thus serving a vital ecological purpose for many plant and animal species. However, these environments face many threats including damage from vehicles, gravel extraction, invasive plant species, development on river margins, low flow levels and poor water quality (Department of Conservation [DOC], 2006).

There has been less research on braided rivers than other types of rivers, such as single-channel meandering rivers (Sambrook Smith et al., 2006). Much braided river research has focused on understanding their geomorphological structures and processes such as sediment transport (e.g. Ashmore, 1993; Huggenberger & Regli, 2006; Nicholas et al., 2006). Many studies up to the early 1990s consisted of laboratory-based modelling of the braiding process (Ashmore, 1982; Young & Davies, 1991) and field studies of small reaches of valley-confined systems (Ferguson et al., 1992). Beginning in the mid-1990s there were advances in numerical models to estimate the braiding process in reaches, remote sensing, and the quantification of river morphology and morphological change using digital elevation models (DEM), which allowed for the first time the visualisation and analysis of the morphology of large braided rivers (Hicks et al., 2006; Lane, 2006). While some early studies (Scott & Thorpe, 1986; Van't Woudt & Nicolle, 1978) investigated groundwater-surface water interactions in braided river systems, this is a relatively new and underexplored area of research.

2.3 Background literature

Research examining methods to characterise groundwater-surface water interactions is still comparatively young as a sub-field of hydrology. Furthermore, there is a scarcity of studies specifically examining these phenomena in braided rivers and their associated aquifers. As detailed above, braided river environments are typically highly conductive and geologically heterogeneous with dynamic flow levels and geomorphology. These complexities may help explain the lack of studies that have attempted to identify (and more specifically quantify) these interactions (Thomas, 2010). Considerably more research has been applied in other environments such as lakes, estuaries, small streams and other types of rivers (e.g. Cey et al., 1998; Landon et al., 2001; Lee, 1977). Traditionally, flow gauging has been a popular method for identifying gaining and losing reaches of braided rivers (e.g. Burbery & Ritson, 2010; Farrow, 2016; Riegler, 2012). Various methods employing Darcy’s Law have been attempted in braided rivers including the use of groundwater wells and piezometers to determine aquifer properties such as hydraulic gradient and conductivity (e.g. Botting, 2010; Burbery & Ritson, 2010; Cheng et al., 2010). Environmental tracers have been used to delineate groundwater and surface water flow paths as well as quantify flux. These methods have included stable isotopes (Blackstock, 2011; Botting, 2010), radon (Close et al., 2014), chloride (Cantafio & Ryan, 2014), and alkalinity and silica (Rodgers et al., 2004). Modelling using software packages such as MODFLOW and FEFLOW have been used in various studies of braided river groundwater-surface water interactions (Baalousha, 2012; Gusyev et al., 2012; Scott & Thorley, 2009) to understand processes such as groundwater flow paths, contaminant transport and the impact of water abstraction on surface and groundwater levels. These models have used both the Stream (STR) and River (RIV) packages in MODFLOW; set head-dependent boundary conditions in FEFLOW; and custom models to account for braided river-specific characteristics.

There are several studies whose methodologies are of particular relevance to this current research. Some of the studies referenced below have been conducted in braided rivers, while many have been conducted in other environments (e.g. other types of streams, lakes, estuaries) and still provide useful information on the various methodologies. A number of studies have been carried out using mini-piezometers including Brodie et al. (2009); Hughes (2006); and Cey et al. (1998), with some specifically in braided rivers, such as Malard et al. (2001); and Acuña and Tockner (2009). Several researchers have used vertical temperature probes of varying design to explore groundwater-surface water exchange (e.g. Briggs et al., 2014; Cranswick et al., 2014; Gordon et al., 2013; Naranjo & Turcotte, 2015), as well as studies specifically conducted in braided rivers (Acuña & Tockner, 2009; Malard et al., 2001; Tonolla et al., 2010). Prior research on the chosen study methods will be discussed further in Chapter 3.

Given the wide range of methods available for investigating groundwater-surface water interactions, there are various important considerations when selecting methods for a study, and further, there are special considerations relevant to braided river environments. The most appropriate methods will depend on physical and hydrological conditions in the given setting and scale of interaction (LaBaugh & Rosenberry, 2008).

The objectives of the study will greatly influence which methods are most applicable. If only qualitative information is required, this could be obtained by methods such as mapping the locations of wet and dry reaches of a river at low flows, or identifying where there is mixing between groundwater and surface water based on chemical or heat tracers. If quantitative data is needed, such as the volume and rate of contaminant movement, this may be obtained by measuring flux rates from radon or temperature signal analysis, or by calculating the hydraulic gradient using piezometers. Researchers have developed flux quantification techniques for many of the methods discussed in this thesis, but it is important to consider inputs required to calculate seepage, such as streambed hydraulic conductivity. If direct water samples are needed, tools to consider could include groundwater wells or piezometers. Water samples and flux rates can also be obtained using seepage meters, a common method used for estimating groundwater-surface water interactions typically based on the design proposed by Lee (1977). However, these devices have various limitations as discussed in previous studies (Brodie et al., 2009; Cey et al., 1998; Kelly & Murdoch, 2003), which indicate their application in braided rivers would be difficult and less effective than other methods.

It is important to appropriately match the scale of the data required with the methods being used. This should include the consideration of both spatial (Figure 2.4) and temporal scales. If regional or catchment-scale information is desired, methods such as pumping tests, flow gauging, stable isotope analysis, solute tracers, chemical analysis or airborne thermal imaging are among the most applicable methods. It is important to recognise that it may be difficult to accurately characterise groundwater-surface water interactions in highly heterogeneous environments based on broad-scale methods. At the reach scale, oxygen-18 or radon analysis could be appropriate methods (Lovett, 2015). At a point scale, streambed piezometers and vertical temperature profiles can be useful. With finer resolution methods, there may be issues with up-scaling the data because many closely spaced measurements are needed, and it is difficult to distinguish between regional groundwater discharge and hyporheic zone flow (Lovett, 2015). While point-scale data may be desired, it may be impractical to carry out the large number of measurements necessary on a wider scale (such as in a large river). Temporal scale variabilities are also important to consider. Groundwater-surface water interactions can change daily, seasonally and in response to external factors such as releases of excess irrigation water into rivers. Some methods may require that all sampling be completed within a short time period so that the data is representative of similar conditions. For instance, concurrent flow gauging, where reaches in a river are gauged on the same day, will generally produce the most reliable representation of baseflow conditions, as flows can change daily (Farrow, 2016). Depending on the analysis method, temperature profiling often needs to be continuous over a period of time to remove the influence of diurnal fluctuations (Passadore et al., 2015).

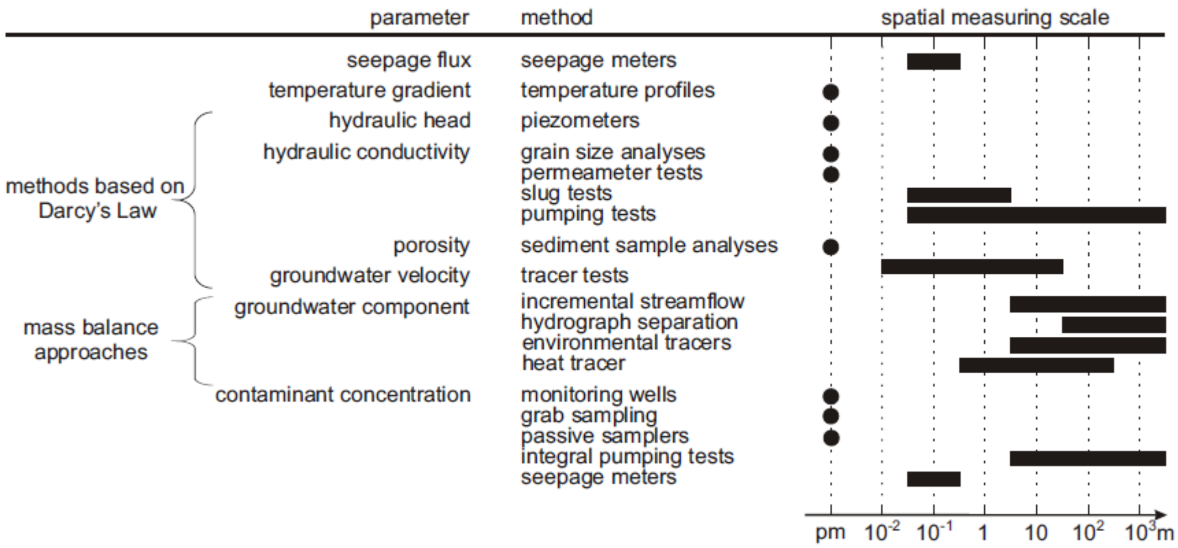


Figure 2.4. Relevant spatial scales for various methods used to measure groundwater-surface water interactions. (pm = point scale measurements). Source: Kalbus et al. (2006).

Conceptualisation and quantification of hydrogeological systems is generally associated with a degree of uncertainty. The degrees of accuracy of measurements can vary based on many factors including sampling protocol, laboratory analysis, lack of information (e.g. aquifer properties) or the nature of the method chosen. The degree of accuracy required by the study objectives should be carefully considered when choosing the appropriate method. Likewise, the level of accuracy and confidence in results should be discussed in conjunction with study results.

Site-specific characteristics will largely determine the most appropriate methods to use. The geology, topography, hydrochemistry, hydrology and hydrogeology of the study site will need to be considered. Factors such as geologic complexity, chemical components of the soils and surface and ground waters, aquifer properties, and climate should be taken into account. There are various practical considerations such as the availability of groundwater wells, river access and feasibility of techniques. Inputs and outputs to groundwater and surface water may need to be considered, such as abstraction for irrigation or industrial discharges.

As with any study, the available resources will greatly influence the types of methods selected. Techniques vary in cost depending on materials needed, installation requirements or analysis methods. Mini-piezometers, for example, would be on the inexpensive end of this range, while airborne thermal imaging is a more expensive method (although it is decreasing in cost with improved drone technology). Time is a key consideration, and this can range widely. For instance, with groundwater modelling, analytical models are less time consuming and can serve as a good “first pass” model, where numerical models require more time to create yet produce more precise results. Some field techniques, such as mini-piezometers, while simple and inexpensive, may be quite time consuming to carry out given the significant number of measurements required to obtain a representative sample. If many replicate samples are required to obtain representative data for an area, it may be cheaper to use remote sensing or another broad-scale method. Analysis requirements should be considered when evaluating the merits of particular methods. Some chemical sampling for example may require expensive laboratory analysis and then subsequent statistical analysis, whereas other methods such as flow gauging require minimal processing of data. The availability of data relevant to the study site will be important to consider. For instance, aquifer properties may need to be known to carry out calculations or modelling. Or historical sampling records may be needed to compare long-term trends.

Despite these various considerations involved in choosing the appropriate methods for carrying out investigations of groundwater-surface water interactions, according to Landon (2001), the number of measurements made may be more important for obtaining reliable data than the type of methods chosen given the spatial variability in hydraulic conductivity of streambeds. Also, as demonstrated in the various studies discussed in this thesis, rarely did researchers rely on a single method to explore groundwater-surface water exchange. As Kalbus et al. (2006) conclude in their comprehensive review of techniques for investigating groundwater-surface water exchange, more reliable results for estimating fluxes between groundwater and surface water may be obtained by combining multiple methods at various scales.

2.4 Hakatere/Ashburton River background

2.4.1 Study location

The location for this study is on the Hakatere/Ashburton River on the South Island of New Zealand in the Canterbury region (Figure 2.5). The Hakatere/Ashburton River is a gravel-bed braided river, which begins as two branches that meet approximately 21 km northwest of the coast in the town of Ashburton. The South Branch begins at the Ashburton Glacier on Mt Arrowsmith (2,795 m) and flows for 113 km before its confluence with the North Branch, which flows from Godley Peak (2,087 m) for 98 km to the confluence. The catchment of the South Branch to the confluence with the North Branch is approximately 1,030 km^2 and is glacially fed, whereas the North Branch is foothills fed and its catchment is approximately 515 km^2 (Gabites, 2006). The river flows southeast in a depression created by the alluvial fans of the Rakaia River to the north and Rangitata River to the south (Irrigation New Zealand, 2017).

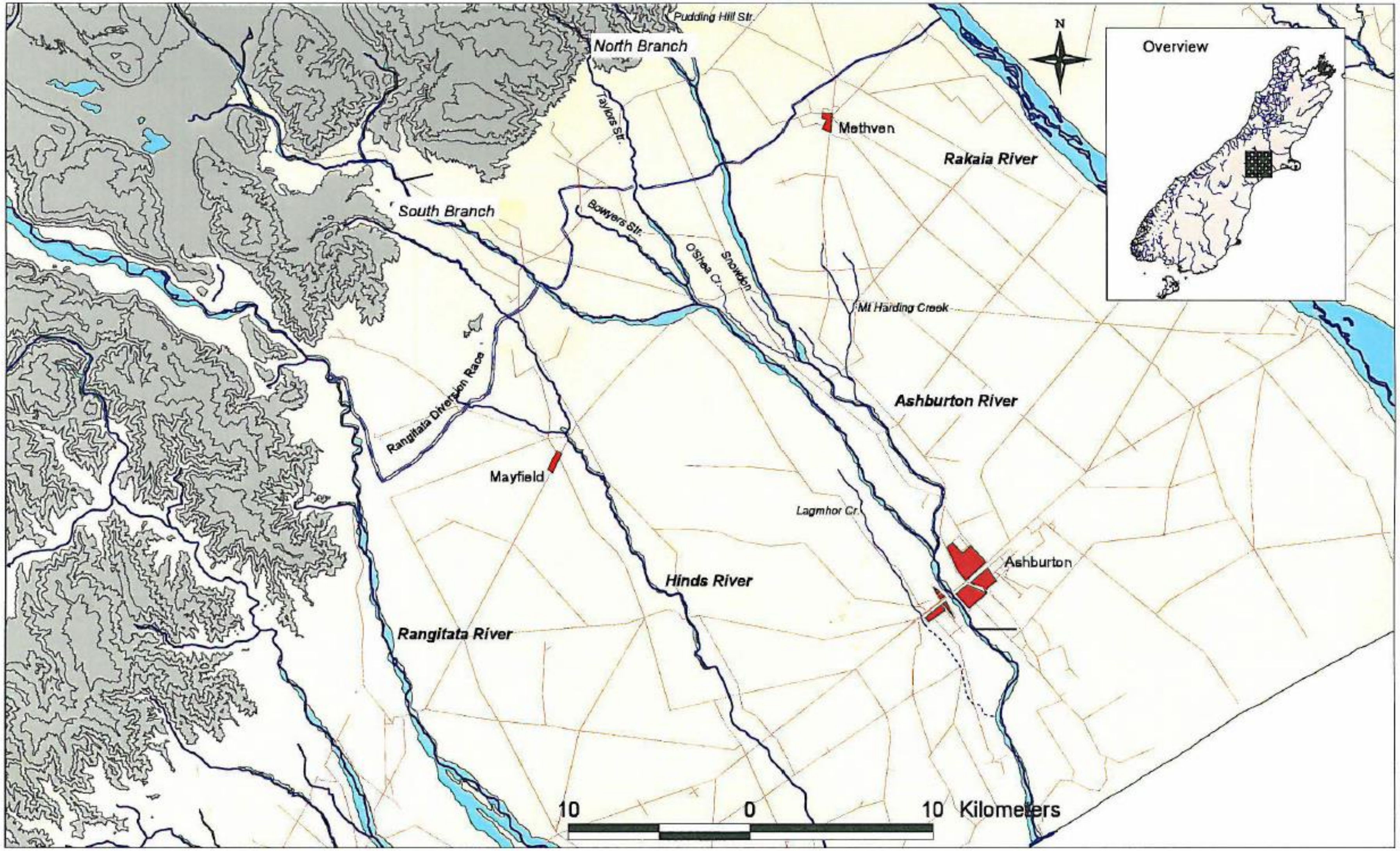


Figure 2.5. Map of study area. Source: Horrell (2001).

The Hakatere/Ashburton River is located on the Canterbury Plains, which extend from the foothills of the Southern Alps east to the coast of the South Island, and from Waipara in the north to Timaru in the south (Durney et al., 2014). In terms of geology, the basement rock consists of late Palaeozoic to Mesozoic Torlesse Supergroup greywacke sandstones and argillites (Dommisse, 2006) overlain by Tertiary marine and terrestrial sediments (Hanson & Abraham, 2013). Over these units, the plains are mainly comprised of late Quaternary gravel, sand and mud that were deposited by alpine braided rivers in coalescing alluvial fans during glacial periods (Dommisse, 2006; GNS Science, 2014). These Quaternary deposits extend to over 600 m deep (Hanson & Abraham, 2013). The upper catchment of the South Branch of the Hakatere/Ashburton River also contains late Cretaceous volcanics around Mount Somers (GNS Science, 2014). The Ashburton/Rangitata plains to the south of the Hakatere/Ashburton River reach about 300 m above sea level in the foothills and slope down to the coast at an average 0.6% gradient (Hanson & Abraham, 2013).

In regard to soil types, the upper and mid catchments of the Hakatere/Ashburton River largely consist of moderate to well-draining silty loam (Landcare Research New Zealand Limited, 2017). These soils have a low water-holding capacity and thus are heavily irrigated (Hanson & Abraham, 2013). Adjacent to the riverbeds, the soils are less freely draining, as they contain loess from wind-blown river sediments (Hanson & Abraham, 2013). In the lower catchment, on the south side of the river from State Highway 1 to the coast, the soils are mainly poorly draining clays with some silty loam (Landcare Research New Zealand Limited, 2017). The north side of the river in the lower catchment consists of better draining silty loams (Landcare Research New Zealand Limited, 2017).

Average annual rainfall in the Hakatere/Ashburton catchment varies widely with up to 3,000 mm in the upper South Branch catchment (Gabites, 2006), as low as 650 mm at the coast and about 1000 mm in the foothills (Scott, 2004).

The Quaternary gravels deposited on the Canterbury Plains form a productive groundwater aquifer throughout the region. While earlier studies have proposed multiple aquifers on the plains, the prevailing thought now is that it is a single gravel and sand aquifer consisting of local semi-confined layers of silty clays (Aitchison-Earl & Ritson, 2013; Hanson & Abraham, 2013). The aquifer was formed by deposition of sandy gravels from braided rivers in lenses and channels, with some lenses comprised of clay-bound or poorly sorted gravels, which are less permeable (Hanson & Abraham, 2013). It is thought that the majority of groundwater flow occurs in these highly permeable gravel channels (Davey, 2006). Average depth to the water table is 5 m, but it can reach 50 m below ground level in the upper plains (Hanson & Abraham, 2013). Groundwater levels are higher near the rivers and lower in the centre of the plains (Thorley et al., 2010). Towards the coast, the depth to groundwater is generally 1 to 2 m and serves as a source of inflow to coastal streams (Durney et al., 2014). Regionally, groundwater flows southeast from the foothills towards the coast (Durney et al., 2014). Inland there is a strong downwards hydraulic gradient, whereas towards the coast, groundwater flows upwards (Thorley et al., 2010).

The groundwater-surface water interactions of the Hakatere/Ashburton River and surrounding groundwater are complex. Thirteen concurrent flow gaugings were carried out on the South Branch from 1995-2007, and the results of this show that the river has both gaining and losing reaches throughout its course (Durney et al., 2014; Horrell, 2001). Surrounding the river, there are numerous groundwater-fed springs; stockwater and irrigation races; and manmade drains, which both recharge the river in places and are fed by river water in other locations. Aitchison-Earl (2000) carried out a comprehensive mapping of springs in the Hakatere/Ashburton catchment, in which springs were located and classified based on morphology, variability and geology. Figure 2.6 includes a map of these springs, and the area of focus in the current study mainly falls into Zone 4 labelled on the map: Westerfield, Lagmhor[1]/Langdons Creek.

[1] Note that "Lagmhor" is incorrectly spelled in Figure 2.6.

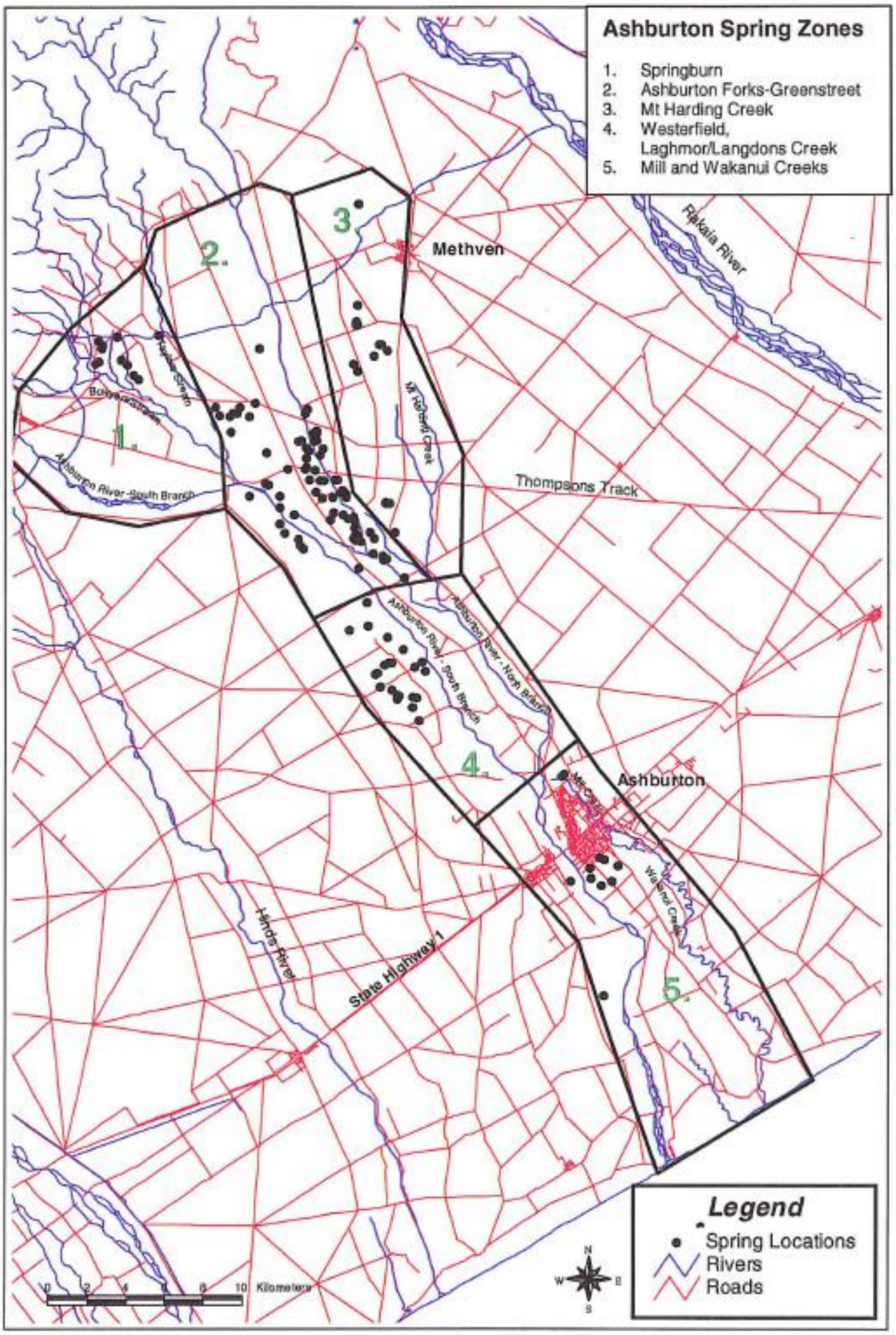


Figure 2.6. Springs of the Hakatere/Ashburton catchment. Source: Aitchison-Earl (2000).

The complex groundwater and surface water dynamics of the catchment are complicated by numerous takes and discharges to the river, mainly for irrigation and stock water. In a 2001

Environment Canterbury (ECan) report, Horrell accounted for inflows and outflows to the river, shedding light on the intricate network of surface water channels flowing in and out of the river. This report included a map estimating gains and losses along the river, which has proved very useful for subsequent investigations of the catchment (Figure 2.7).

Figure 2.7. Estimated gains (in blue) and losses (in yellow) in the Hakatere/Ashburton River. Source: Horrell (2008).

Based on results from previous studies, groundwater flow directions around the river appear to be complex, and outstanding questions in this regard in part prompted the current study. As seen in Figure 2.7, the North Branch has a net loss of flow for most of its length above the North/South Branch confluence. Current thought is that it loses flow to groundwater to the northeast and to the South Branch (personal communication, P. Durney 24 Jan 2017; G. Horrell Apr 2017). In addition to gaining flow from the North Branch, it is believed that the South Branch is recharged from several sources including upstream losses from Bowyers Stream, Taylors Stream and the South Branch, which re-emerge in lower reaches of the South Branch, and Greenstreet Irrigation border dykes (personal communication, P. Durney 24 Jan 2017; G. Horrell Apr 2017). The South Branch of the Hakatere/Ashburton appears to lose groundwater across the Ashburton-Rangitata plains, where groundwater generally appears to flow from northwest to southeast (Hanson & Abraham, 2013) and is believed to be a source of recharge to the Rangitata River and the Hinds River to the south (Dommisse, 2007).

In addition to the inherent complexities of this groundwater and surface water system, there are many manmade changes that have affected the natural flow of the river and surrounding groundwater. This includes extensive wetland draining and the subsequent construction of channelised drains across the plains; irrigation (both in terms of abstraction and land-based recharge); willow planting along riverbanks; modification of river channels for flood protection; and abstraction of ground and surface water for domestic and stockwater use (Horrell, 2001).

The Hakatere/Ashburton River is within one of the ten water management zones designated by the Canterbury Water Management Strategy (Figure 2.8) (Environment Canterbury [ECan], 2010). The Ashburton Zone is bordered by two large braided rivers—the Rakaia River in the north and the Rangitata River in the south—and is divided by the Hakatere/Ashburton and Hinds rivers (Environment Canterbury [ECan], 2017a). The zone is intensively farmed and is one of the most agriculturally productive regions in New Zealand (Environment Canterbury [ECan], 2017a). However, these land use activities have presented challenges in the management of freshwater resources. Groundwater in the zone is overallocated—i.e. more water use has been granted in resource consents than the regional council has deemed sustainable. Surface water allocations from the Hakatere/Ashburton River are also under pressure, with no new consents for surface water or stream-depleting groundwater permits to be allocated until a new minimum flow level of 10 m^3/s at State Highway 1 goes into effect in 2033 (Environment Canterbury [ECan], 2017b). Water quality has also declined, with high nitrate and phosphate levels, mainly in the lower catchment, as well as high faecal contamination, making several recreational sites regularly unsafe for swimming (Ashburton Zone Committee, 2011). High nitrate levels in groundwater are also an issue, with a large proportion of monitored wells in the Ashburton Zone exceeding the Maximum Acceptable Value for drinking water compared to other areas of Canterbury (Wong, 2016).

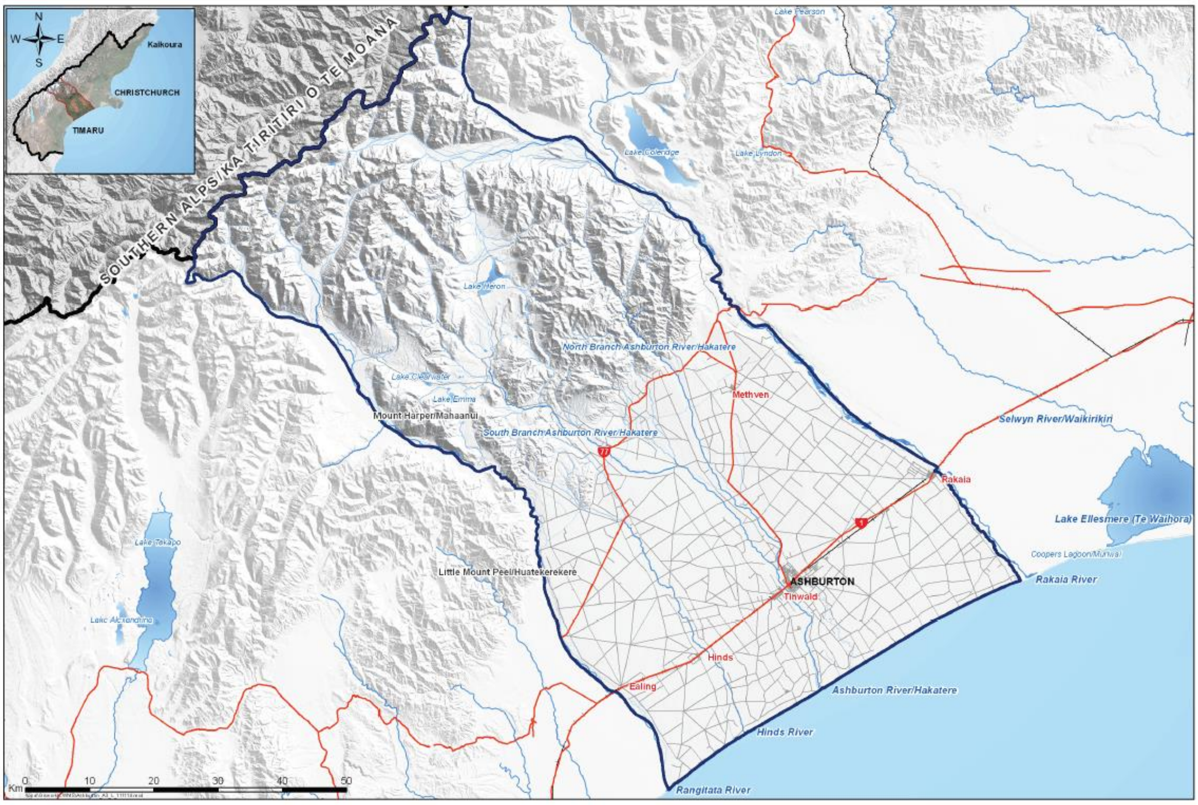


Figure 2.8. Ashburton Water Management Zone. Source: Ashburton Zone Committee (2011).

As with many other freshwater bodies globally, the Hakatere/Ashburton River is important to a number of stakeholders. In addition to the intensive land use in the catchment, the river and surrounding plains are home to many native plants and birds, several of which are critically threatened (see Appendix E for a list of all birds observed at the study sites during this research). This river is of significant cultural importance to the local Māori tribe, Ngāi Tahu. It also has various recreational values including fishing, swimming, walking and mountain biking along the river and its banks.

The specific area of focus for this study is the South Branch of the Hakatere/Ashburton River. The regional council, Environment Canterbury, identified that there were outstanding questions regarding groundwater-surface water interactions in this area, which prompted the current study. This study attempts to improve the understanding of these processes on the South Branch. In addition, the chemical analysis component of this study will hopefully add to the knowledge base to address groundwater and surface water quality issues in the Ashburton Zone.

Environment Canterbury identified a specific area of interest on the South Branch of the river—from Mt Somers (at State Highway 72) south to the confluence with the North Branch. Two study sites along this reach of the South Branch were chosen for this study: Sheates Road/Ollivers Road and Mill Road/Blacks Road (Figures 2.9-2.12). There were various factors to consider in selecting adequate study sites including vehicle access (ideally at road crossings or through private property); size of gravel at sites (larger gravel would be more difficult for installation of equipment); suitability of river channels (i.e. calm and shallow); and popularity of site with river users (less frequently used sites were preferred). Also, sites that had been used for previous data collection would prove useful for comparison of findings. The sites at Sheates Road/Ollivers Road and Mill Road/Blacks Road were selected because they best fit the criteria set out above. Two sites were selected as this would allow for comparison between the two locations. Additional sites were not tested due to restrictions in time and resources.

Figure 2.9. Map of study sites on South Branch of the Hakatere/Ashburton River.

Figure 2.10. Ollivers Rd site, 27 Sept 2017. Photo: Katie Coluccio

Figure 2.11. Sheates Rd site, 15 Nov 2017. Photo: Katie Coluccio

Figure 2.12. Blacks Rd site looking towards Mill Rd site, 16 June 2017. Photo: Katie Coluccio

This study builds on previous research carried out on the Hakatere/Ashburton River and surrounding area. This prior work includes regular monitoring carried out by Environment Canterbury, such as flow gauging, rainfall measurement and water quality testing. Key resources drawn on for this investigation included in-depth studies such as early reports on groundwater resources in the area (Scott & Thorpe, 1986); chemical analysis of groundwater on the Ashburton-Rangitata Plain (Hanson & Abraham, 2013); groundwater level mapping and river flow measurements (Aitchison-Earl & Ritson, 2013); and numeric modelling (Durney et al., 2014). This study will also build on previous thesis work in the area such as that by Riegler (2012).

Chapter 3. Methods

3.1 Overview

This thesis research used a multi-method approach to investigate groundwater-surface water interactions. More specifically, these methods were used to attempt to locate areas of mixing of groundwater and surface water and quantify the amount of seepage through the streambed. A key focus of this study was to evaluate the effectiveness of various methods for use in measuring groundwater-surface water exchange in gravel-bed braided river environments. As discussed in Section 2.2, while there has been a considerable amount of research into groundwater-surface water interactions in many types of waterbodies, particularly in the past 20 years, braided rivers have been underexplored. A possible explanation for this gap in the literature is that braided rivers present many challenges that may be more easily overcome or not relevant in other types of waterways such as wetlands, lakes and small streams. Characteristics including coarse gravel beds, heterogeneous substrate, channel shifting and highly variable flow levels make it difficult to choose appropriate methods for carrying out these types of investigations in braided rivers.

The methods used in this study were groundwater well observations (via mini-piezometers and existing wells), vertical temperature probes and physicochemical sampling. Carrying out differential flow gauging was also an objective of this study, but to date has not been done due to flow in the river being too high. This range of methods includes those traditionally used for these types of investigations in braided rivers (i.e. groundwater wells and flow gauging), as well as methods that have not previously been applied in this type of setting (i.e. vertical temperature probes). Each method was selected and designed in a way to cope with the challenges of braided rivers to the furthest extent possible. This chapter discusses this process of method selection and study design. For equipment that needed to be built, the following sections detail their design, construction and testing. The ways in which these tools were used, i.e. the specific experiments and data collection methods, are also discussed here.

It is also relevant to note that seepage meters were initially considered for this study. The proposed design was an open-bottomed cylinder installed into the streambed that would directly measure seepage flux such as those used in Brodie et al. (2009), Cey et al. (1998) and Lee (1977). Based on results from previous studies (Brodie et al., 2009; Cey et al., 1998; Landon et al., 2001; Lee & Cherry, 1978; Thomas, 2010) and advice received (P. Aitchison-Earl, personal communication, 3 Feb 2017), it would have been difficult or impossible to install a seepage meter into the coarse gravel streambed in the high-energy environments of the study sites and achieve the seal necessary to measure seepage.

It should be noted that this thesis frequently refers to the right and left sides or banks of the river. This refers to the right and left banks when one is facing downstream in the river.

3.2 Groundwater well observations

Measuring groundwater levels in wells is a common method for gaining insight into groundwater processes and aquifer properties. Observations of groundwater levels are often used to aid in the understanding of groundwater-surface water interactions, and there have been several studies conducted in braided rivers (e.g. Acuña & Tockner, 2009; Burbery & Ritson, 2010; Chen, 2007; Larned et al., 2008; Riegler, 2012). In terms of specific methods that can be used for measurements, existing groundwater wells near rivers can be useful for conducting these types of studies, particularly given the high cost of drilling groundwater wells. Piezometers are also often used both on land and in rivers to measure groundwater pressure and water levels. In previous studies, groundwater level observations have rarely been used in isolation, and are typically coupled with other methods. This study combined the use of mini-piezometers and existing groundwater wells to conduct various tests including water level measurements, physicochemical sampling and slug tests.

3.2.1 Mini-piezometers

3.2.1.1 Background

Mini-piezometers have been used in many studies of groundwater-surface water exchange (e.g. Acuña & Tockner, 2009; Brodie et al., 2009; Cey et al., 1998; Hughes, 2006; Malard et al., 2001) and offer a simple and inexpensive method for obtaining groundwater level and pressure data. A piezometer is a cased hole with a screen at a fixed interval. They allow for the observation of groundwater conditions at a single point in an aquifer and are used to measure shallow groundwater, typically no deeper than 2 m below the streambed (Brodie et al., 2007). They are easy and quick to install in most locations, and the analysis of their measurements is generally straightforward (Kalbus et al., 2006). They can be used in small-scale applications and in detailed surveys in heterogeneous environments (Kalbus et al., 2006). However, measurements at a study site must be taken at the same time to be representative of similar flow conditions (Kalbus et al., 2006).

In studies of groundwater-surface water interactions, mini-piezometers can be used to determine the gradient between the depth to the water table and river stage height (Brodie et al., 2007). The hydraulic gradient indicates the direction of seepage at a point scale. Seepage flux can be calculated if the hydraulic conductivity of the streambed is known or closely estimated. Mini-piezometers can also be used to collect water samples and perform aquifer tests. The mini-piezometers installed in this study were used for these various purposes.

3.2.1.2 Design of equipment

Various iterations of mini-piezometer design have been attempted in previous studies, such as those made from PVC or metal pipe with holes drilled at the bottom for screening (Acuña & Tockner, 2009; Hughes, 2006; Malard et al., 2001), or flexible tubing with a screen attached to the bottom (e.g. Cey et al., 1998; Grimon, 2010; Lee & Cherry, 1978; Thomas, 2010).

The coarse gravel material in the bed of the Hakatere/Ashburton River posed a challenge for the installation of the mini-piezometers used in this study. As the majority of previous studies involving mini-piezometers were not in gravel-bed rivers, this research involved the design and construction of wells specifically suited for this study site.

There were various initial design considerations including the robustness of equipment to withstand installation into gravel and river flooding; length and diameter of wells; and installation and removal methods. The piezometers were designed in a way that all parts could be reused, whereas other designs have included single-use materials such as drive points that remain in the waterbody after piezometer removal. Mild steel was chosen for the casing material for the piezometers. Stainless steel was initially tested as a casing material, however it was more difficult to cut the well screen than mild steel. Mild steel was also less expensive. Steel pipe with a 25-mm inner diameter (34-mm outer diameter) was selected. There were several reasons for this choice. Upon reviewing previous studies and receiving advice from various people who had used mini-piezometers in the past (e.g. Hughes, 2006), it was apparent that a smaller diameter pipe would be easier to install in the coarse gravels than a larger diameter pipe. In addition, a 25-mm inner diameter was required to fit a jack hammer that was used for installation. Also, there was careful consideration as to the sizes of probes and meters that would need to be lowered into the piezometer to carry out tests and sampling.

Length of the piezometer casing was extensively debated and considered. There were several practical factors: If the casing exceeded a certain length it would be impossible to transport or install it as a single piece, and thus would require multiple casing sections. Arguably this would also nullify this tool being considered a “mini-piezometer” in its traditional definition. It was agreed that a single casing would be the preferable option.

While many previous studies have installed mini-piezometers to quite shallow depths into the streambed, often less than one metre, (Acuña & Tockner, 2009; Cey et al., 1998; Malard et al., 2001), there was concern that installation to less than a metre would not be a sufficient depth given the thickness of the hyporheic zone was unknown. If the piezometers were not installed to an adequate depth, the water sampled may have been surface water flow within the streambed rather than groundwater. A scoping exercise was conducted to attempt to identify the depth to groundwater below the ground surface on the riverbanks. Given the permeability and imprecise boundaries of the river, there was an expectation that very shallow groundwater would be chemically similar to the river water (i.e. shallow sub-surface river flow). A 3-m long, 25-mm inner diameter mild steel pipe was used as a well casing for this scoping exercise. It was screened with vertical slots (using a 1.5-mm wide, 125-mm diameter cutting blade) from approximately 50 cm from the top to the bottom of the pipe. The end that was screened was welded into a point. This casing was driven into the river margin (approximately 2 m from the river's edge) to an approximate depth of 2.5 m. Once installed, water was pumped using a Solinst Peristaltic Pump (Solinst Canada Ltd., Ontario, Canada) to develop the well. A PVC pipe (20-mm electrical conduit) with a 20-cm screen, insulated with foam insulation tape on either end of the screen to block throughflow in the steel casing (Figure 3.1), was inserted into the casing to sample the well at discrete intervals. This test was conducted on one side of the river at both study sites (Ollivers Rd and Blacks Rd) and the results were compared to readings in nearby shallow groundwater wells. The results of this scoping exercise are discussed in Section 4.1. The scoping exercise was inconclusive in regard to defining the boundary of river water and groundwater on the river margin. Following this, a casing length of three metres was selected for the mini-piezometers, as this was the longest piece of casing that could be installed before needing to use separate sections of steel. The bottom 20-30 cm of the pipes were screened using a using a 1.5-mm wide, 125-mm diameter cutting blade, and the ends were welded into points. A cap was constructed from stainless steel bar to insert in the top of the casing during installation to prevent deformation of the casing.

Figure 3.1. PVC screen for interval sampler. Photo: Katie Coluccio

The installation and removal methods for the mini-piezometers were carefully considered, as it was expected that these would be difficult tasks in a coarse gravel riverbed. The steel casings were installed using a handheld steel fence post driver. For difficult installations, a petrol-powered fence post driver was used, which made installation significantly faster. Each mini-piezometer was installed in September 2017 to approximately 2.5 m below the ground surface or riverbed (Figure 3.2). After installation each well was pumped with a Solinst Peristaltic Pump (Solinst Canada Ltd., Ontario, Canada) to develop the well (Figure 3.3). They were pumped until all sediment was removed from the wells and the water was clear. Removal of the mini-piezometers involved the use of a high-lift jack (in some cases two) to lift the steel casing out of the ground and river (Figure 3.4).

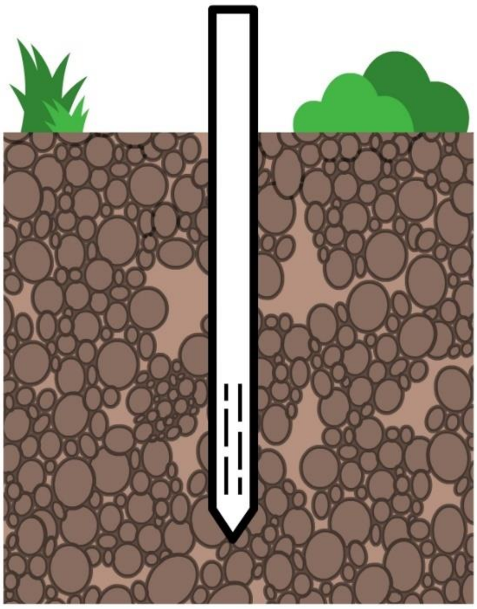


Figure 3.2. Conceptual diagram of mini-piezometer construction and installation. A 3-m long, 25-mm inner diameter (34-mm outer diameter) steel pipe was screen at the bottom 30 cm. The bottom of the pipe was welded into a point. The piezometers were installed to 2.5 m deep in the river and on the river margins. Image source: Steve Coluccio

Figure 3.3. Pumping a newly installed mini-piezometer to clear all sediment from the well and establish a hydraulic connection with the substrate. Photo: Katie Coluccio

Figure 3.4. A high-lift jack was used to remove the mini-piezometers. Photo: Katie Coluccio

The following materials were required for construction, installation and removal of the mini-piezometers:

- Mild steel pipe (inner diameter = 25 mm, outer diameter = 34 mm)
- Mild steel rod for end cap
- Steel fence-post driver
- Petrol-powered post driver
- High-lift jacks (x2)
- For interval sampler: PVC electrical conduit (20-mm diameter), foam insulation tape, electrical tape

3.2.1.3 Site selection

Mini-piezometers can be installed into streambeds in various configurations such as nested (at varying depths); transects (in a line along the groundwater flow path, typically perpendicular to the stream); or in networks (at different locations and screened in the same aquifer) (Brodie et al., 2007). It is essential to consider the objectives of the study when choosing an arrangement for mini-piezometers. It is important to highlight that these wells only provide information in one location in a riverbed or groundwater aquifer; thus many piezometers may be required to obtain a broader understanding of a study area (Cey et al., 1998). This is likely of particular relevance in braided rivers where the substrate is often comprised of heterogeneous grain sizes, and water does not move at the same rate in all locations.

The mini-piezometers in the current study were installed in two horizontal transects perpendicular to the river (Figures 3.5-3.7). The locations of each piezometer are detailed in Appendix A. Each transect consisted of five piezometers installed in the following locations: one on both the right and left banks approximately 5-10 m from the river's edge; one on both the right and left banks between 150-500 m from the river's edge; and one piezometer in the river. The piezometers were arranged in this way to identify whether there was a horizontal hydraulic gradient between the river and shallow groundwater by measuring water levels in the wells. The piezometers installed on the banks were screened in the bottom 20-30 cm of the steel casing, while the piezometers installed in the riverbed were screened from 50 cm to the bottom of the casing.

Figure 3.5. Mini-piezometer locations at the Mill Rd/Blacks Rd study site. Map source: Google My Maps

Figure 3.6. Mini-piezometer locations at the Sheates Rd/Ollivers Rd study site. Map source: Google My Maps

Figure 3.7. Mini-piezometer (on right side of photo) installed on the river bank at Ollivers Rd. Photo: Katie Coluccio

There were several general considerations for installation locations. The sites needed to reasonably clear of obstructions so that installation and testing could be carried out. The ability to park close by would greatly increase the efficiency of the work, particularly when sampling multiple wells in one day. For the piezometers installed in the river, they needed to be in a place that was relatively calm and accessible, and these were both installed on gravel bars. There was also consideration as to the location and number of piezometers needed to measure a representative river stage height. Both study sites consist of multiple wet channels and the river stage height varies across the channels based on the elevation of the gravels. Arguably several averaged river stage height measurements taken horizontally across the river channels would be the most representative stage height. Due to limitation of resources, only one piezometer was installed into the river, and the main consideration of this river piezometer location was access.

3.2.1.4 Piezometric surveys

Groundwater level data can be used to identify the hydraulic gradient in a location, which can reveal groundwater discharge to streams and river recharge into aquifers. The underlying principle is that if groundwater levels in a well are higher than the river (a positive hydraulic gradient), the river is considered to be gaining, and groundwater flows into the river. Conversely, where river levels are higher than the groundwater level (a negative hydraulic gradient), these are considered losing reaches where river water is flowing into the groundwater (Figure 2.1).

Piezometric surveys were carried out on seven occasions between September and November 2017 where the water levels in the mini-piezometers were measured. All water level measurements needed to occur on the same day, preferably as closely timed as possible, to compare between wells and river stage heights (Kalbus et al., 2006). Water levels were measured with a Solinst 102M Mini Water Level Meter (Solinst Canada Ltd., Ontario, Canada) and recorded to millimetre accuracy. As will be discussed in Section 3.2.3, a differential GPS survey was carried out to obtain accurate vertical elevations of the wells so that the water levels could be compared.

3.2.1.5 Physicochemical sampling

Physical (temperature) and chemical (conductivity, pH, nitrate-nitrogen, dissolved reactive phosphorus) parameters were sampled in the mini-piezometers for several reasons. Temperature, conductivity and pH are routinely measured while groundwater wells are purged to ensure that all stagnant water is removed from the wells. Nitrate-nitrogen (NO_3-N) and dissolved reactive phosphorus (DRP) were analysed to determine whether shallow groundwater is a source of contamination to the river or vice versa. Finally, these five parameters may also be useful as tracers to identify sources of water as either groundwater or surface water. Many previous studies have measured these same physical and chemical parameters to better understand surface water-groundwater exchange (e.g. Burbery & Ritson, 2010; Chitsazan et al., 2014; Hitchcock, 2014; Larned et al., 2015; Soulsby et al., 2004).

Three rounds of physicochemical sampling were carried out. Each well was purged using a Solinst Peristaltic Pump (Solinst Canada Ltd., Ontario, Canada) following the New Zealand national protocol for groundwater sampling (Daughney et al., 2006). Each well was purged in excess of three well volumes, and as the well was pumped, pH, temperature and conductivity of the purged water were monitored using a Thermo Scientific Orion Star A329 Portable Multiparameter Meter (Thermo Scientific, Waltham, MA, USA) and a Hach HQ40D Portable Multi Meter (Hach, Loveland, CO, USA). Once these parameters stabilised and the pumped water was largely free of sediment, a water sample was taken for analysis. The samples were filtered using a 33-mm diameter Millipore Millex-HA 0.45-µm membrane filter (Figure 3.8) and then NO_3-N and PO_4 (measured as orthophosphate and later converted to DRP) were analysed in the field using a Hach DR890 Portable Colorimeter (Hach, Loveland, CO, USA). Both parameters were analysed in triplicate at a minimum, and additional replicates were tested in the event of anomalous readings. After the mini-piezometers were purged, pH, conductivity and temperature were also measured in the wells using the Orion probe.

Figure 3.8. Filtering a water sample before analysing for nitrate-nitrogen and phosphate. All chemical analysis was conducted in the field. Photo: Katie Coluccio

3.2.1.6 Slug testing

Slug tests were performed on the piezometers installed on the riverbanks to determine the hydraulic conductivity (*K*) of the aquifer substrate. Slug tests involve the lowering or raising of the water level in a well using a “slug” (of water, air or a weight), the removal of the slug, and the measurement of the water levels as the water recovers to its initial level.

Based on advice received early in this study, a pneumatic slug test was used due to the anticipated high permeability of the gravel aquifer (personal communication, MS Srinivasan, 13 Apr 2017; P. Durney, 18 Apr 2017). The high transmissivity of the aquifer would cause the water in the well to quickly recover to its original level once the slug was removed. To obtain sufficient data to calculate hydraulic conductivity, the slug removal would need to be precisely controlled and a data logger that took multiple readings per second would be needed.

Rising head tests were carried out in November 2017 using a pneumatic slug testing device designed and built by University of Canterbury Engineering Geology student Ben Michell (Michell, 2017). The slug test device (Figures 3.9-3.11) was attached and sealed to the top of each mini-piezometer, and air was pumped into the well to push the water level down to the desired level. A Level TROLL 500 Data Logger (In-Situ Inc., Fort Collins, CO, USA) was used to measure pressure and water levels in the piezometers. In-Situ's Win-Situ 5 software was used to perform the slug tests. Once the slug tests were initiated in Win-Situ, the air was removed from the well and the TROLL was programmed to take four readings per second. Each test was ended once the water level returned to the initial depth. Three slug tests were performed on each well. The two mini-piezometers installed in the riverbeds were not slug tested as they were screened from the surface of the riverbed to the bottom of the well. Any air injected into the well would immediately flow out of the screen and the water level would not be lowered.

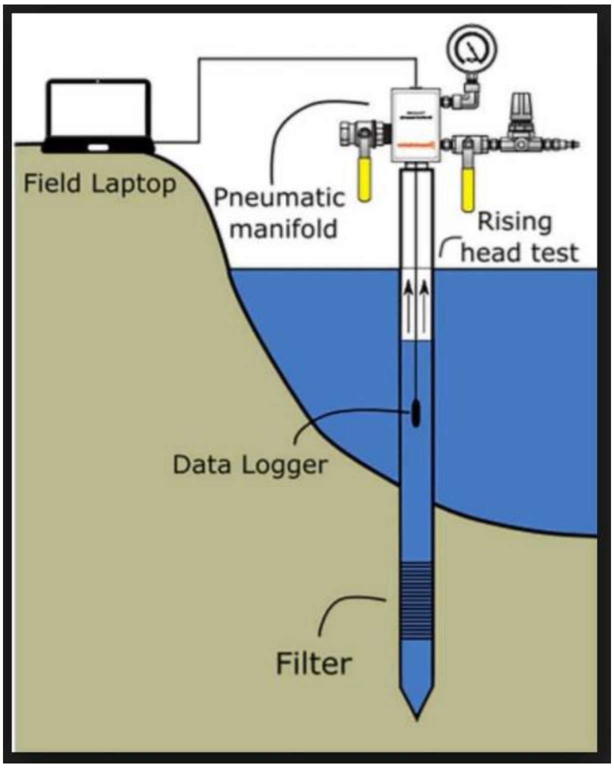


Figure 3.9. Conceptual diagram of pneumatic slug test device connected to a mini-piezometer. A data logger is placed in the well and connected to a laptop to monitor the results in real time. Air is injected through the pneumatic manifold to lower the water level in the well. A rising head test is performed by releasing the air and measuring the water level as it returns to the initial level. Source: Geoprobe Systems (2016)

Figure 3.10. Pneumatic slug test device installed on the top of a mini-piezometer at the Mill Rd study site. Photo: Katie Coluccio

Figure 3.11. Conducting a slug test on a mini-piezometer at the Mill Rd study site. The pneumatic slug test device is attached to the top of the piezometer. A cable runs through the slug test device connecting the data logger in the well to the computer in the photo. A bicycle pump (right side of photo) is used to pump air into the well and lower the water level. Photo: Katie Coluccio

3.2.2 Existing groundwater wells

To enhance the data gathered from the mini-piezometers, shallow groundwater wells close to the river were also sampled.

3.2.2.1 Well selection criteria

There were several considerations when selecting appropriate wells for sampling. Well locations and details were obtained from Canterbury Maps (canterburymaps.govt.nz). Shallow wells (<20 m) were targeted for sampling as these would be more likely to be hydraulically connected to the river and chemically similar to the water collected from the mini-piezometers. Wells closest to the river were examined first for suitability, and as those were eliminated as prospects the search moved further from the river. The wells were selected so that they were closely aligned with the piezometer transects. Some wells could not be located as either they no longer existed or were buried. Some were unsuitable for sampling as their large diameters would have made purging impractical. An inability to contact the well owners was also a common reason wells were removed from the list of potentials. Four groundwater wells were selected (see Appendix A for locations and details). The wells ranged from approximately 2-16 m deep and were located between 0.4 and 1.8 km away from the edge of the river. Some wells were not surveyed for the full extent of the study for various reasons, which will be explained in Chapter 4.

3.2.2.2 Piezometric surveys

As with the mini-piezometers, water levels were measured in the groundwater wells to identify whether there was a hydraulic gradient between shallow groundwater and the river.

3.2.2.3 Physicochemical sampling

Three of the four groundwater wells were analysed for physical (temperature) and chemical (conductivity, pH, nitrate-nitrogen, dissolved reactive phosphorus) parameters using the same methods as for the mini-piezometers as described in section 3.2.1.5. The well that was not chemically analysed (Mill Rd Pipe), was not technically a well—it was an open-bottomed PVC pipe installed to about 2 m deep into the ground. It was suitable for water level measurements, but not for chemical analysis.

3.2.3 Differential GPS survey

To effectively compare the water levels in the river and groundwater wells, highly accurate vertical elevations needed to be obtained. Errors associated with determining hydraulic gradients can be significant where wells have been installed within a few metres of the river's edge or the hydraulic gradient is small, and a very accurate measurement of well casing elevations can help overcome these potential issues (Rosenberry & LaBaugh, 2008).

A differential GPS survey was completed in October 2017 using a Trimble R10 GNSS System (Trimble, Inc., Sunnyvale, CA, USA) (Figure 3.12). A Fast Static Survey was carried out with a minimum occupation time of 10 minutes at each observation point. All of the mini-piezometers and groundwater wells were surveyed. Three LINZ (Land Information New Zealand) geodetic marks were also measured on the day of the survey as reference points. Two wells were located in sheds, so to measure these points, a laser level was used in conjunction with the Trimble R10.

After post-processing of the data, for all but one well (K37/0133), the average vertical accuracy of the GPS coordinates was 18 mm and the average horizontal accuracy was 11 mm. For an unknown reason, well K37/0133 could not be post-processed. This may be due to this well's close proximity to sheds on two sides of the well causing a lack of satellite data during the survey.

Figure 3.12. The author conducting the differential GPS survey at the Sheates Rd/Ollivers Rd study site. Photo: Peter Joynt

3.3 Temperature probes

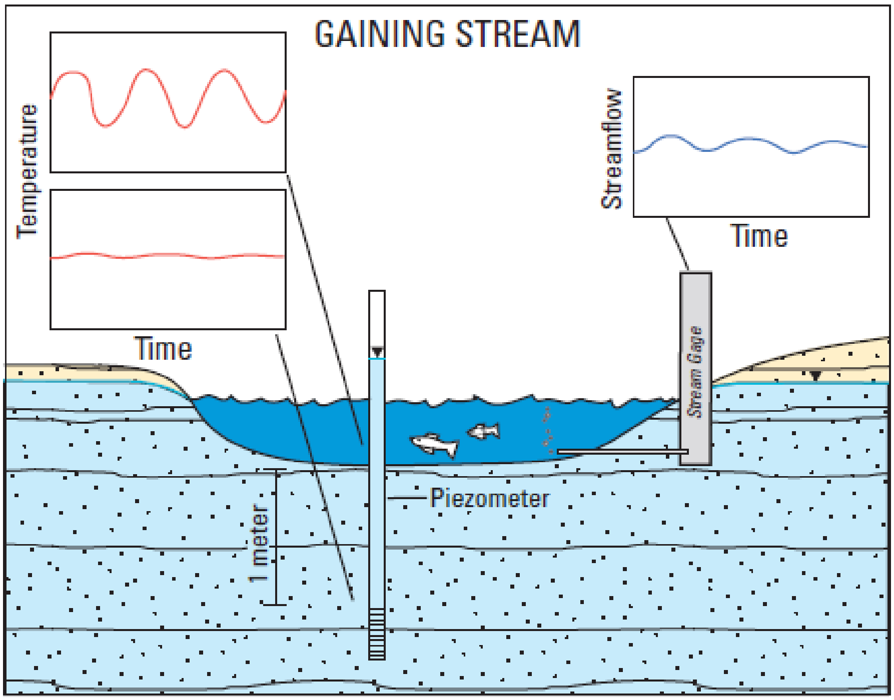
3.3.1 Background

Temperature has been used in a number of studies to characterise groundwater-surface water interactions in braided rivers (e.g. Acuña & Tockner, 2009; Close, 2014; Tonolla et al., 2010). Heat flows between surface water and groundwater systems and thus can serve as a natural tracer for exchange (Constantz et al., 2008) without the real or perceived issues with chemical tracers. The use of temperature as a tracer relies on the measurement of temperature differentials and it is considered a very robust parameter to measure (Constantz et al., 2008). In most locations, during winter and summer months, there is a discernible difference in groundwater and surface water temperatures. In summer, groundwater will typically be colder than surface water, whereas in winter, groundwater is usually warmer. Generally, groundwater temperature is more stable, whereas surface water temperatures change diurnally and seasonally (Kalbus et al., 2006). Heat tracer methods can be used to identify discharge and recharge zones as well as quantify the flux of water moving between groundwater and surface water systems (Kalbus et al., 2006).

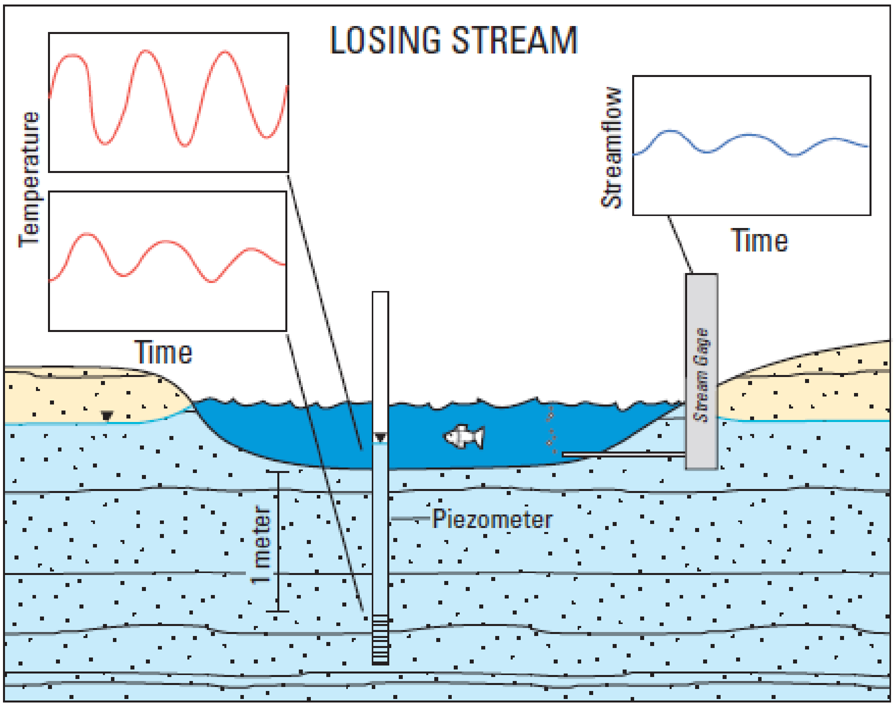
There are several methods involving temperature sensing that range in complexity, scale and cost. Temperature readings can be measured simply using a temperature probe either in-stream or in piezometers. Vertical and horizontal temperature profiles can be measured both in-stream and on river margins using groundwater wells. Fibre-optic temperature sensing can be used to measure temperature profiles in rivers at the reach scale. On the more expensive end of the spectrum, airborne thermal infrared imaging can be used to obtain temperature profiles of rivers on a large scale.

Vertical temperature probes have been used in several studies as a comparatively inexpensive and easy-to-install tool for measuring groundwater-surface water exchange (e.g. Fanelli & Lautz, 2008; Gordon et al., 2013). Temperature sensors are mounted at a minimum of two different depths on a probe and inserted into the streambed to measure the vertical temperature variation (Constantz et al., 2008; Irvine et al., 2017). Various types of sensors can be used to measure temperature profiles such as thermocouples, HOBO temperature loggers (Onset Computer Corporation, Bourne, MA); and iButton sensors (Maxim Integrated, San Jose, CA). iButtons have been increasingly used in studies (e.g. Cranswick et al., 2014; Naranjo & Turcotte, 2015) due to their low cost, robustness, small size, high degree of accuracy and laboratory calibration (Irvine et al., 2017; Naranjo & Turcotte, 2015).

The analysis of diurnal temperature signals can be useful for identifying locations of groundwater-surface exchange (Irvine et al., 2017) and has been used in a number of studies of this nature (Briggs et al., 2014; Hatch et al., 2006; Rau et al., 2010; Stonestrom & Constantz, 2003). The temperature of surface water bodies varies throughout the course of a day, with the highest temperatures in the day and lowest temperatures at night. On the other hand, groundwater beyond a certain depth generally does not have diurnal temperature variation. Thus, the analysis of these daily temperature variations can indicate where groundwater and surface water are mixing, both in gaining and losing reaches of rivers (Figure 3.13). Diurnal signal analysis also allows for the calculation of the seepage flux, i.e. the rate of water upwelling or downwelling through the streambed.



(a)



(b)

Figure 3.13. Conceptual drawing of diurnal temperature variation in a (a) gaining stream and (b) losing stream. Source: Constantz et al. (2008).

There are some limitations to consider with the use of temperature as a tracer for groundwater-surface water exchange. Some assumptions are necessary such as that flow is vertical and the substrate is homogeneous and isotropic (Constantz et al., 2008). Transient flow can create errors in diurnal signal analysis as well as “edge effects” at the beginning and end of the time series (Hatch et al., 2006).

3.3.2 Design and construction

The temperature probes used in this study consisted of a novel design based on tools used in previous studies (Briggs et al., 2014; Cranswick et al., 2014; Fanelli & Lautz, 2008; Gordon et al., 2013; Malard et al., 2001; Naranjo & Turcotte, 2015; Tonina et al., 2014). The casing for the four temperature probes was constructed from 1.8-m long, 25-mm inner diameter (34-mm outer diameter) mild steel pipe. This diameter pipe was selected as it was wide enough to fit the temperature sensors yet narrow enough to install in coarse gravels. The casing extended 1.1 m below where the sensors were mounted to ensure there was sufficient pipe driven into the streambed so the probes would withstand high river flows. Fifty centimetres of the pipe were left above the streambed and spray painted to ensure other river users could see the probes to avoid accidents. PVC 20-mm electrical conduit was used for the probes, and holes were drilled at 5-cm spacing where the temperature sensors were inserted into the PVC. Four sensors were inserted into each probe. Insulation foam was sprayed into the pipe between each sensor in the PVC pipe to prevent throughflow of water. Also, insulation foam was wrapped around the PVC pipe above and below each sensor to prevent water flow between the PVC pipe and steel casing. The foam tape was covered with duct tape and petroleum jelly to facilitate insertion and removal of the PVC pipe in the steel casing. Vertical slots were cut in the steel to create a screen around the temperature sensors (Figure 3.14).

Figure 3.14. Close-up view of a vertical temperature probe (left). Four iButtons are mounted at 5-cm spacing and separated by insulation tape. The PVC probe is inserted into the steel casing with vertical screening (right). Photo: Katie Coluccio

The 1922L model iButton (±0.5°C accuracy, 0.0625°C resolution, Maxim Integrated, San Jose, CA) was selected for this study over other iButton models as it has the resolution necessary for diurnal temperature analysis (Irvine et al., 2017), and has been used in several similar studies (e.g. Briggs et al., 2014; Gordon et al., 2013). While waterproof iButtons are available, many studies have used alternative forms of waterproofing (such as silicone or plastic) without affecting the accuracy of the sensor (Irvine et al., 2017). In this study, the iButtons were waterproofed with several coatings of Plasti Dip, a rubber coating available at automotive supply stores. Using Plasti Dip for waterproofing had several advantages: it was inexpensive and the coating could be easily removed so the iButtons could be inserted into the USB reader.

The following materials were required to build the temperature probes:

- Mild steel pipe (25-mm inner diameter, 34-mm outer diameter)
- PVC electrical conduit (20-mm diameter)
- iButtons (model 1922L)
- iButton USB cable and reader
- Plasti Dip aerosol spray
- Insulation foam tape
- PVC/Duct tape
- Petroleum jelly

3.3.3 Location selection

Temperature probes were installed on the right and left sides of the river at the two study sites (Figures 3.15-3.16). The same sampling locations (±10 m) were used for each data collection run with the exception of the probe at Mill Road. The location of this probe changed after the first data collection run (4-11 July 2017), as this location was no longer accessible due to the river being too high to cross and no access from the bank where the probe had first been installed. The locations of the probes are detailed in Appendix A. There were several considerations when selecting potential temperature probe locations. The installation sites needed to be accessible in a range of flow conditions. Sites with calm and shallow channels would make access easier and reduce the likelihood of the probes washing away in floods. However, the channel where each probe was installed needed to remain flowing for the duration of the sampling, so it was necessary to select a location that would not run dry. Installation of the probes away from potential flood debris, such as vegetation, would be advantageous in ensuring the probes would withstand storms (Figures 3.17-3.18).

Figure 3.15. Temperature probe sampling locations at the Mill Rd/Blacks Rd site. Map source: Google My Maps

Figure 3.16. Temperature probe sampling locations at the Sheates Rd/Ollivers Rd site. Map source: Google My Maps

Figure 3.17. Temperature probe installation at the Sheates Rd site. Photo: Katie Coluccio

Figure 3.18. Temperature probe site at Blacks Rd before installation. Relatively shallow and calm channels at the edges of the river were selected for installation. Photo: Katie Coluccio

3.3.4 Sampling design

Diurnal signal analysis requires temperature measurements at a minimum of two different depths (Constantz et al., 2008). To provide more flexibility in data analysis and a backup in case of sensor failure, four iButtons were used in each probe (Irvine et al., 2017).

There are various considerations in deciding the appropriate depths that sensors are installed into the streambed. The direction and magnitude of exchange (i.e. seepage upwards or downwards through the streambed) will influence the diurnal signal pattern at each depth in the streambed. In an area of upwelling, it is necessary to have a closely spaced sensor pair installed to a shallow depth in the streambed. This is because the diurnal signal will be dampened by the upwelling groundwater. In contrast, in a downwelling site, the diurnal signal will propagate deeper into the streambed, and thus deeper temperature sensors or wider spacing between sensors will be possible. In sites where the direction of seepage is unknown, it is advisable to install at least one closely spaced pair just below the top of the streambed (Irvine et al., 2017). As the direction of seepage was unknown at the study sites, the four iButtons were installed at depths of 1, 6, 11 and 16 cm from the top of the streambed (Figure 3.19).

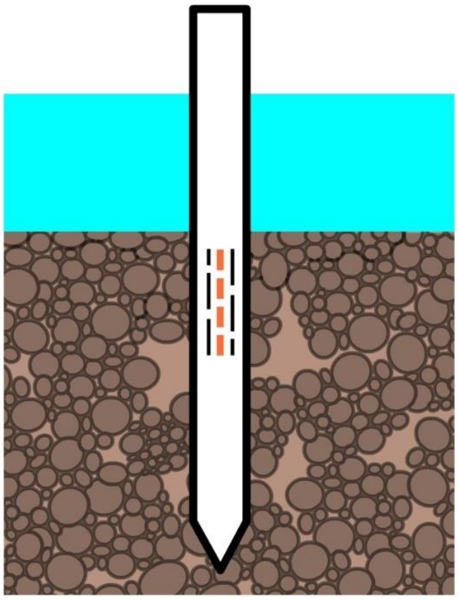


Figure 3.19. Conceptual diagram of the vertical temperature probes. The probes were installed into the streambed so the iButtons were at depths of 1, 6, 11 and 16 cm below the top of the streambed. Image source: Steve Coluccio

Three data collection runs were carried out during July-October 2017 that ranged in length from seven to 22 days. The iButtons were programmed to take continuous temperature readings at 10-minute intervals. While it would have been possible to take readings at coarser intervals, this may have missed minimum and maximum temperatures, leading to significant errors in data analysis (Irvine et al., 2017).

3.4 Flow gauging

3.4.1 Background

Differential flow gauging can be used to identify gaining and losing reaches of rivers by measuring streamflow in cross sections and then calculating the difference in flow between the cross sections (Kalbus et al., 2006). If there is an increase or decrease in flow, this can be considered as a gaining or losing reach, respectively, provided any surface inflows or outflows (e.g. tributary inflows, abstractions) are accurately quantified. Measurements should generally be taken in low flow conditions to eliminate the influence of recent rainfall (Kalbus et al., 2006). Velocity gauging has most often been used in studies of braided rivers, where the rate of flow is measured in cubic metres per second (or cubic feet or litres per second). Flow gauging is suitable for studies at a larger scale, but not for investigating small-scale heterogeneities (Kalbus et al., 2006). Thus, in the current study, flow gauging as a broad-scale method is used to compare results from point-scale data obtained from the mini-piezometers and vertical temperature probes.

Flow gauging is a common method that has been used in hydrological investigations for several decades to measure the rate of flow in rivers. There are a variety of techniques available to measure stream discharge both directly and indirectly including current meters (such as mechanical, propeller-based meters, or Acoustic Doppler Velocimeters (ADV) and Acoustic Doppler Current Profilers (ADCP)); dilution methods; float gauging; structural methods (i.e. developing rating curves based on river height and spot flow measurements); and slope-area methods (e.g. the Manning Equation) (Chappell, n.d.)). Flow gauging has been used in numerous previous investigations of surface water-groundwater exchange in braided rivers such as Larned et al. (2008), Larned at el. (2015), Reigler (2012), Simonds and Sinclair (2002), and Doering et al. (2013).

There are several issues regarding the effectiveness of flow gauging for characterising groundwater-surface water interactions in braided rivers. These types of rivers are typically comprised of heterogeneous materials, and thus there may be small-scale interactions of groundwater and surface water within reaches, and flow gauging is poor at identifying these smaller scale processes (Kalbus et al., 2006). Accurate measurements of flow rates can be compromised by several factors including interference of macrophytes in the streambed, low flow, unclear stream boundaries, high sediment load, or unstable streambeds that permit parafluvial flow (Thomas, 2010). Flow in the parafluvial zone occurs in the area of riverbed that is to some extent annually scoured by flooding (Stanford, 2007). As noted by Close et al. (2014), there is significant uncertainty around estimates of river to groundwater flows solely based on hydraulic measurements, particularly for large braided rivers, as these environments provide various challenges for accurate flow measurements. These systems are difficult to measure because precise flow gauging can only be carried out during low flows and measurement errors can be considerable (Close et al., 2014). In larger rivers, often the measurement error can be greater than the net exchange of groundwater and surface water (LaBaugh & Rosenberry, 2008).

3.4.2 Sampling design

At the time of writing, the flow gauging had not yet been carried out. It is necessary to conduct the gauging at very low flow levels to remove any influence of recent rainfall, and throughout the study period, the river levels did not drop to a sufficiently low level. The plan for the gauging was that it would be carried out immediately upstream and downstream of each of the two sampling sites using a SonTek FlowTracker1 Acoustic Doppler Velocimeter (ADV) (SonTek, San Diego, CA, USA). The net gain or loss of flow would be determined in each of these "seepage runs". A piezometric survey would be carried out on the same day as the gauging, and temperature probe data would be collected concurrently. The data gathered from the piezometric survey and gauging would be used to calculate a streambed conductance value for the two seepage runs.

The following materials are required for the flow gauging:

- SonTek FlowTracker1 Acoustic Doppler Velocimeter (ADV)
- Wading rod
- Measuring tape

Chapter 4. Results

This chapter presents the results from the data collected in this study as well as details of the data analysis carried out.

4.1 Preliminary investigations

As described in section 3.2.1.2, a scoping exercise was carried out on 16 June 2017 to delineate the boundary between river water and groundwater on the river margins of the study sites. A 3-m long steel mini-piezometer that was screened from 50 cm below the top of the casing to the bottom of the pipe was installed to 2.5 m deep. The piezometers were pumped until all sediment was cleared from the wells. Then a PVC pipe was inserted into the steel casing with a 20-cm screen installed at a set depth. The upper and lower parts of the screen were sealed so that pumped water was only pulled through the screen. The position of the screen was changed so that the well could be sampled at different depths. Measurements of temperature, pH and conductivity were taken in the river adjacent to the mini-piezometer location, as well at two nearby shallow groundwater wells (Environment Canterbury Well IDs K36/0033 and K36/0119). Conductivity and pH measurements were taken at the various piezometer depths to compare to the values obtained in the river and groundwater wells. It was not possible to obtain an accurate measurement of temperature in the mini-piezometers, as this would have required a direct measurement of temperature inside the well, rather than measuring the pumped water from the well. Unfortunately, on the day of this scoping exercise a probe that could measure temperature in the well was not available. Results are presented in Table 4.1.

Table 4.1. Results from preliminary investigation to chemically compare water in mini-piezometers, river and shallow groundwater wells

Sampling Location	**Sampling depth below top of well casing (m)**	**Conductivity (µS/cm)**	**pH**	**Comments**
K36/0033	8.23	454	6.72	~850 m from Bowyers Stream (tributary of South Branch)
K36/0119	5.5	110.1	6.19	~350 m from North Branch
River @ Ollivers Rd	N/A	106.2	8.00	
Ollivers Rd Piezometer Interval 1	2.08-2.28	104.4	6.89	
Ollivers Rd Piezometer Interval 2	1.38-1.58	103.2	6.84	
Ollivers Rd Piezometer Interval 3	.88-1.08	99.4	6.51	
Ollivers Rd Piezometer Interval 4	.18-.38	103.6	6.72	
River @ Blacks Rd	N/A	109.1	7.98	
Blacks Rd Piezometer Interval 1	2.08-2.28	102.2	6.34	
Blacks Rd Piezometer Interval 2	1.38-1.58	102.5	6.33	
Blacks Rd Piezometer Interval 3	.88-1.08	102.8	6.31	
Blacks Rd Piezometer Interval 4	.18-.38	102.9	6.33	

4.2 Piezometric surveys

4.2.1 Summary

Seven piezometric surveys were conducted between September and November 2017 and the results of the water level measurements are presented below.

The main purpose of the water level measurements was to calculate the horizontal hydraulic gradient between the wells and the river, both in terms of identifying the direction of flow and its magnitude. As defined in Darcy's Law, the hydraulic gradient is the change in hydraulic head in a given direction:

$$i = \frac{h_1 - h_2}{\Delta l} \tag{1}$$

where i is the hydraulic gradient, h_1 [L] and h_2 [L] are the hydraulic heads at points 1 and 2, respectively, and Δl [L] is the distance between points 1 and 2 (Schwartz & Zhang, 2003). Water flows from a location of higher head to lower head, so in regards to the relationship of river levels and groundwater, in places where the river level is higher than the groundwater level, surface water flows to groundwater, and vice versa (Rosenberry & LaBaugh, 2008). To determine the direction of groundwater flow, the wells must be screened in the same aquifer, and for this study, all wells were screened in the upper unconfined aquifer.

The water level measurements from the piezometric surveys have also been compared with flow levels at three Environment Canterbury-operated recorder sites upstream of the two well transects. In Appendix B, data has been included for a flow recorder on the South Branch of the Hakatere/Ashburton River at Mt Somers, which is approximately 26 km upstream of the study sites. Flow recorder data has also been included for the two main tributaries of the South Branch—Taylors and Bowyers streams—which converge and flow into the South Branch approximately 13 km upstream of the study sites. Flow levels were compared with all wells on the sampling transect, except K37/0133 for which there were not enough measurements to make a comparison.

Results of the piezometric surveys are also plotted against antecedent rainfall in Appendix B. There are two rainfall recorders in the upper South Branch catchment: one at Mt Somers and one at Boundary Creek near the top of the catchment, and both are operated by Environment Canterbury. The well water levels were compared with the sum of rainfall received at these two sites on the day of the survey and the two preceding days.

The piezometric survey results have been organised by the two well transects at Sheates Rd/Ollivers Rd (Table 4.2, Figures 4.1-4.2) and Mill Rd/Blacks Rd (Table 4.3, Figures 4.3-4.4).

4.2.2 Sheates Rd/Ollivers Rd Transect

Table 4.2. Water levels measured during piezometric surveys on the Sheates Rd/Ollivers Rd well transect

Well ID	19-Sep	26-Sep	4-Oct	11-Oct	17-Oct	31-Oct	15-Nov
K37/2382	156.026	155.958	155.928	*	*	*	*
Sheates Far Piezo	156.090	155.917	155.865	156.045	155.909	155.859	155.836
Sheates Close Piezo	156.097	155.904	155.796	156.121	155.929	155.891	155.843
Sheates River Piezo	155.798	155.575	155.467	*	155.526	155.484	155.447
Ollivers Close Piezo	156.177	156.021	155.725	156.115	155.866	155.690	155.558
Ollivers Far Piezo	155.803	155.714	155.540	155.801	155.642	155.502	155.386
K37/0133	162.760	162.771	*	*	*	*	*

Note: * indicates that wells could not be measured on these dates due to access issues. Results are in metres above sea level.

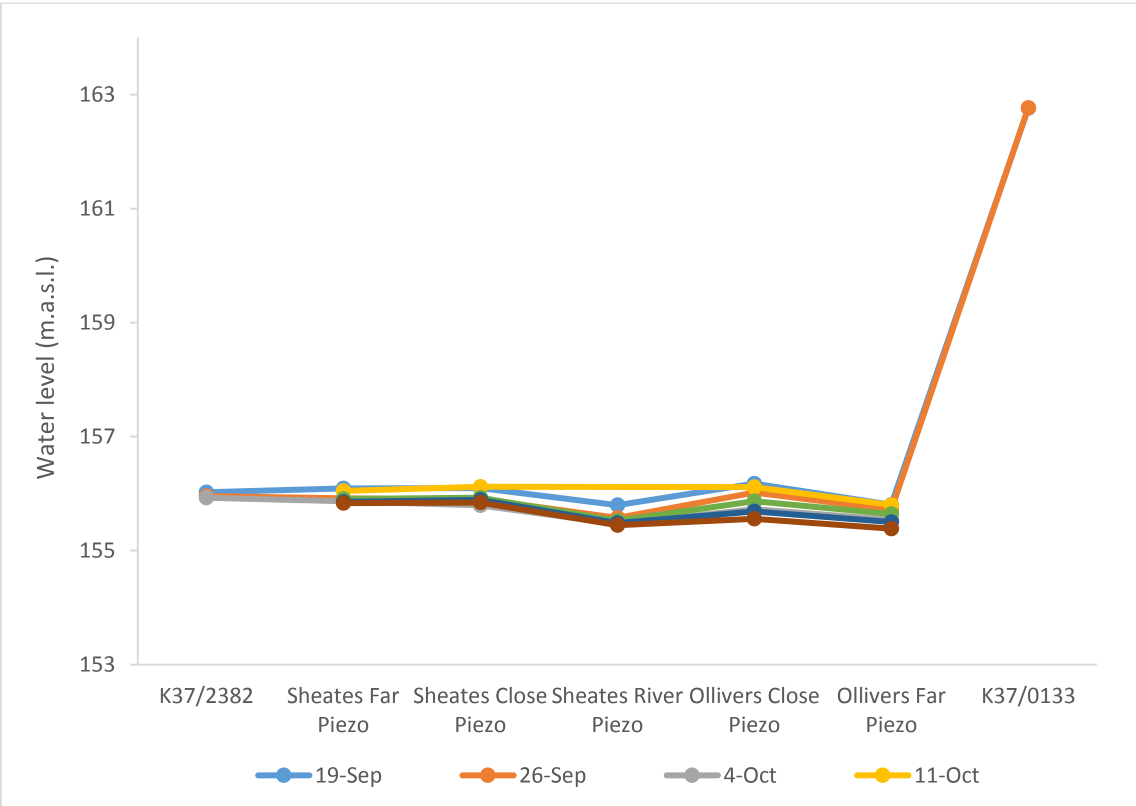


Figure 4.1. Results of seven piezometric surveys on the Sheates Rd/Ollivers Rd well transect. Data points show water levels in metres above sea level and are arranged from south (left side of graph) to north (right side of graph).

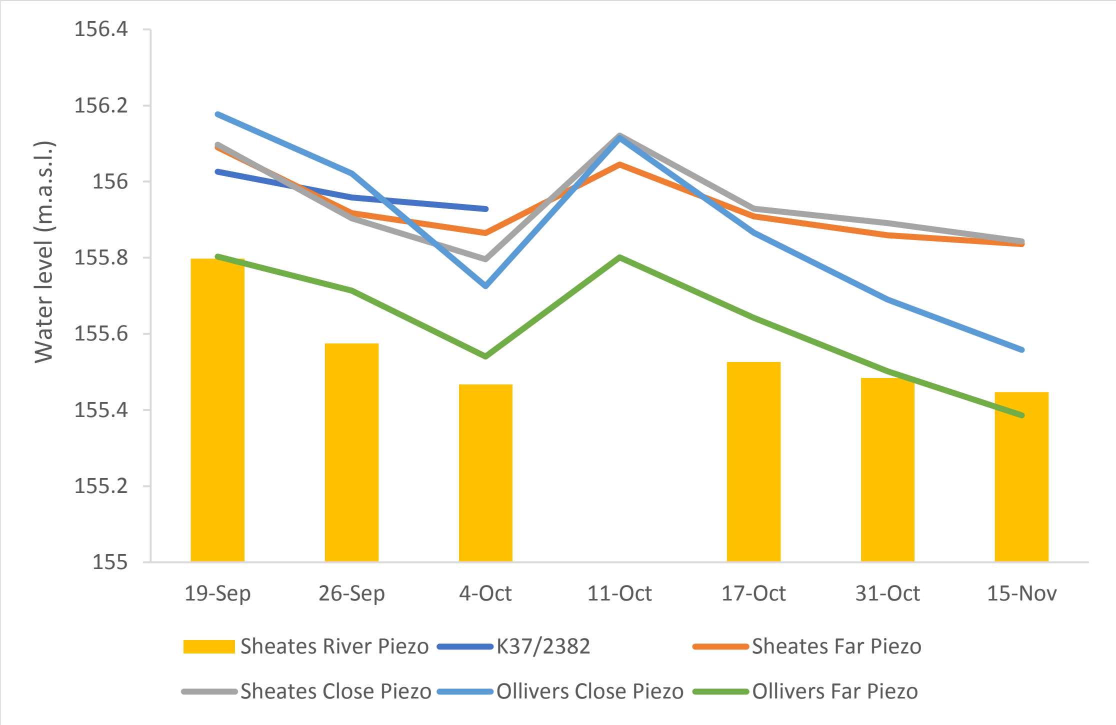


Figure 4.2. Water levels in the Sheates Rd/Ollivers Rd transect plotted against water levels in the river. Note: the river level was not measured on 11 Oct due to a lack of access because of high flows.

4.2.3 Mill Rd/Blacks Rd Transect

Table 4.3. Results from piezometric surveys on the Mill Rd/Blacks Rd well transect

Well ID	19-Sep	26-Sep	4-Oct	11-Oct	17-Oct	31-Oct	15-Nov
K37/3091	135.675	135.490	135.265	135.595	135.345	*	*
Mill Rd Pipe	*	*	135.629	135.962	135.705	135.496	*
Mill Rd Far Piezo	137.873	137.944	137.729	138.041	137.881	137.537	137.478
Mill Rd Close Piezo	138.104	137.923	137.652	138.030	137.816	137.620	137.402
Mill Rd River Piezo	137.919	137.754	137.637	137.810	137.718	137.640	137.527
Blacks Close Piezo	137.325	137.258	137.091	138.268	137.230	137.046	136.925
Blacks Far Piezo	137.642	137.605	137.552	137.782	137.647	137.467	137.340

*Indicates that wells could not be measured on these dates. Results are in metres above sea level.

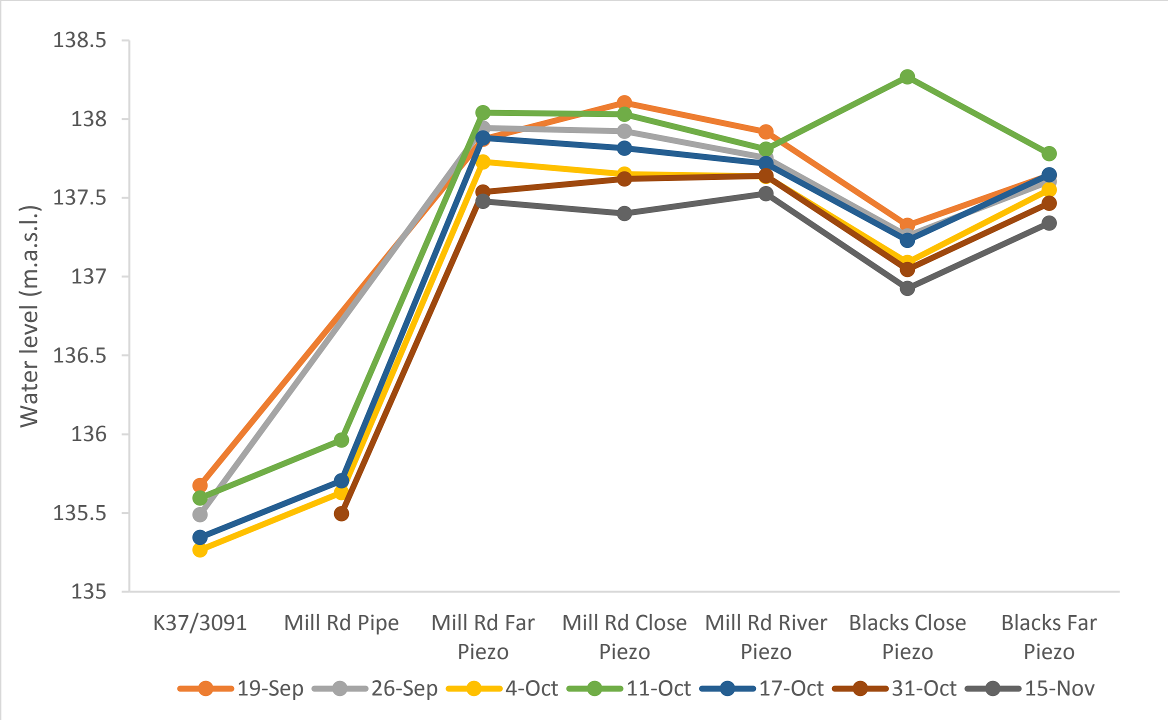


Figure 4.3. Results of seven piezometric surveys on the Mill Rd/Blacks Rd well transect. Data points show water levels in metres above sea level and are arranged from south (left side of graph) to north (right side of graph).

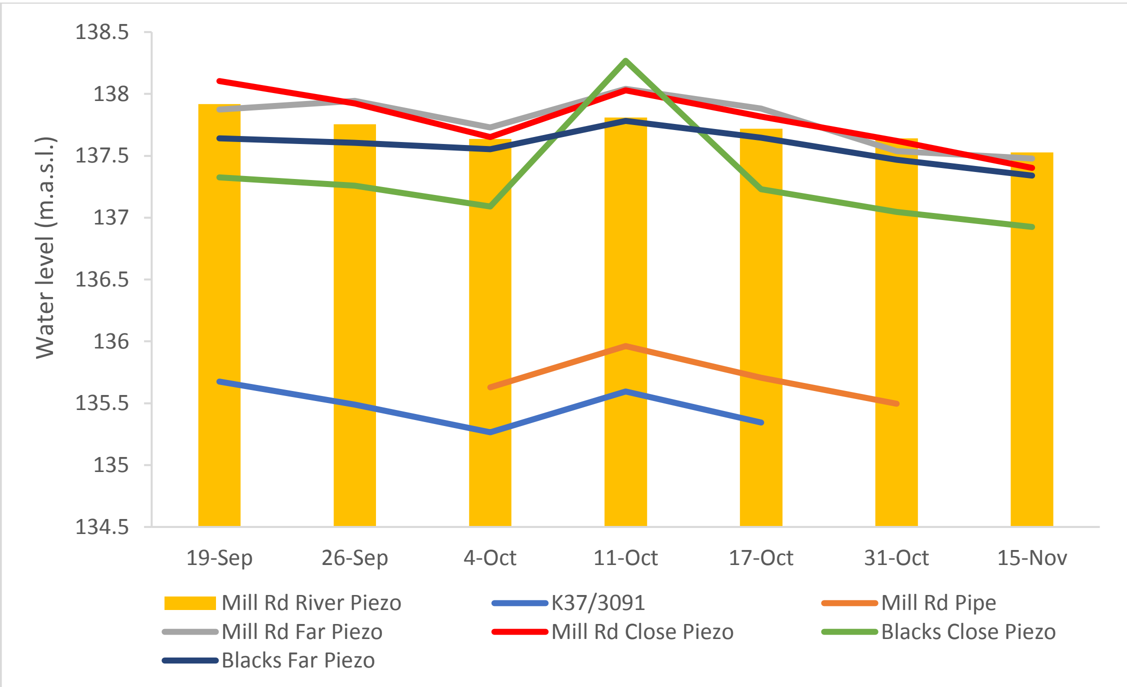


Figure 4.4. Water levels in the Mill Rd/Blacks Rd transect plotted against water levels in the river.

4.3 Slug testing

As discussed in section 3.2.1.6, slug tests were carried out on the eight mini-piezometers installed on the river banks at the study sites on 15 November 2017. Tests at each well were performed in triplicate and the results are presented at the end of this section.

Slug test results were processed using AQTESOLV v.4.5 (HydroSOLVE, Inc.) to obtain hydraulic conductivity (K) values using the parameters listed in Table 4.4. Refer to section 3.2.1.2 for details of well construction. The aquifer parameters required for the slug test analysis were saturated aquifer thickness (b) and the anisotropy ratio (K_v/K_h). Values used for b and K_v/K_h were selected based on Durney et al. (2014), which is a report on a groundwater model of the Hinds-Ashburton plains, and personal communication with P. Durney (21 Nov 2017). The values used in Durney et al. (2014) were based on pumping test data and analysis, and prior studies in the Canterbury region, and literature values. While there is uncertainty around the thickness of the aquifer, Durney et al. (2014) assumes a thickness of 10 m, which has been used here. As for the anisotropy ratio, while a 1:3 ratio is considered conservative, a 1:100 ratio is considered more realistic for the aquifers on the Hakatere/Ashburton River plains (P. Durney, personal communication, 21 Nov 2017), given the high hydraulic conductivity values of the open framework gravels (Dann et al., 2008).

Table 4.4. Well construction and aquifer property parameters assigned for processing of slug test data

Parameter	**Parameter Label**	**Assigned Value**
Saturated aquifer thickness (m)	*b*	10
Anisotropy ratio (K_v/K_h) (unitless)*	K_v/K_h	0.01
Well length (m)		3
Distance to screen (m)	*d*	2.7
Length of well screen (m)	*L*	0.3
Transducer depth (m)	*T*	2.5
Inside radius of well casing (m)	*r (c)*	0.0125
Radius of downhole equipment (m)	*r(eq)*	0.00915
Inside radius of packer (m)	*r(p)*	0
Radius of well screen (m)	*r(w)*	0.0125
Outer radius of well skin (disturbed zone enveloping filter pack) (m)	*r(sk)*	0.0125

*K_v/K_h is the ratio of vertical hydraulic conductivity divided by the horizontal (radial) conductivity.

Slug test responses are often described as overdamped or underdamped. An overdamped response tends to occur in aquifers of low to moderate conductivity (Figure 4.5), whereas underdamped responses may occur in aquifers of high conductivity where the recovery data has an oscillatory pattern (Figure 4.6) (Duffield, n.d.). All of the slug tests had an overdamped response, except the Mill Rd far piezometer, which had an oscillatory (underdamped) response.

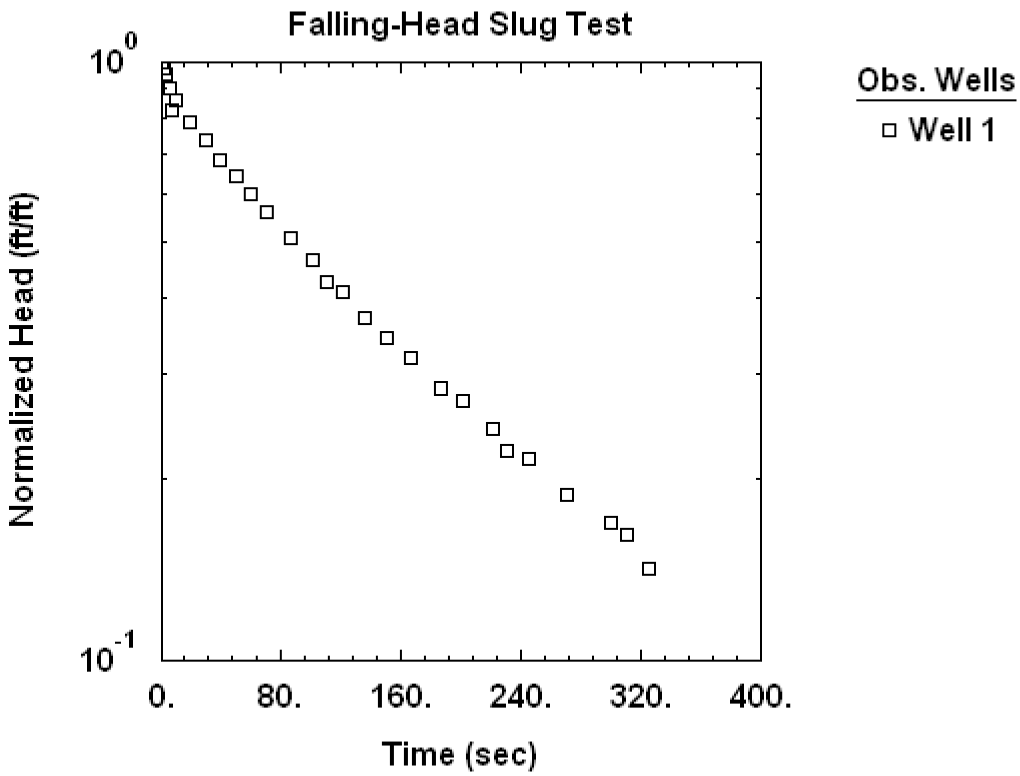


Figure 4.5. Example slug test data from an overdamped response. Source: Duffield (n.d.)

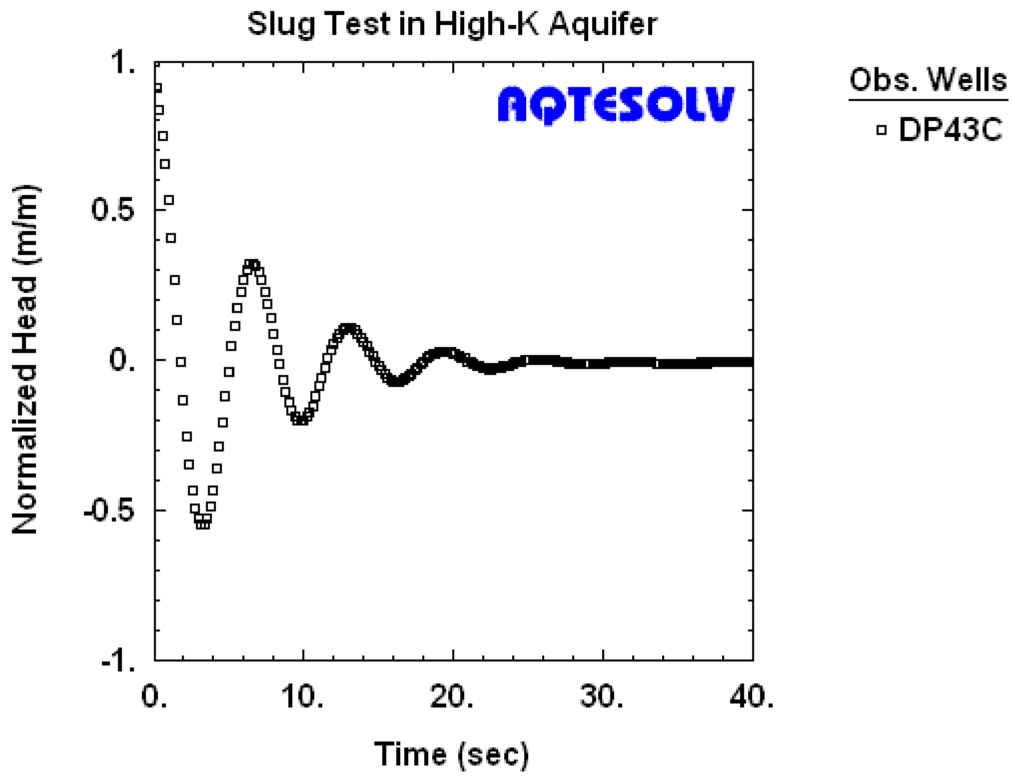


Figure 4.6. Example slug test data from an overdamped response in an aquifer with high hydraulic conductivity. Source: Duffield (n.d.)

The Bouwer-Rice (1976) equation was chosen for calculating the hydraulic conductivity of the overdamped well responses. It is used for wells in unconfined aquifers that either fully or partially penetrate the aquifer. This method involves fitting a straight line to the water-level displacement data recorded during the slug test (*Bouwer and Rice Slug Test Solution for Unconfined Aquifers*, n.d.). The model assumes the following while ignoring aquifer storativity:

- The aquifer has infinite areal extent;
- The aquifer is homogeneous and of uniform thickness;
- The aquifer potentiometric surface is initially horizontal;
- The well is fully or partially penetrating;
- A volume of water (or in the case of this test, air) is injected and removed simultaneously from the well;
- The aquifer is confined or unconfined; and
- The flow is steady (*Bouwer and Rice Slug Test Solution for Unconfined Aquifers*, n.d.).

The Bouwer-Rice model is based on the following equations:

$$\ln(H_0) - \ln(H) = \frac{2K_r L t}{r_{ce}^2 ln(\frac{R_e}{r_{we}})} \quad (2)$$

$$r_{ce} = \sqrt{(1 - n_e)r_c^2 + n_e r_w^2} \quad (3)$$

$$r_{we} = r_w \sqrt{\frac{K_z}{K_r}} \quad (4)$$

where

- H is displacement at time t [L]
- H_0 is initial displacement at t=0 [L]
- K_r is radial (horizontal) hydraulic conductivity [L/T]
- K_z is vertical hydraulic conductivity [L/T]
- L is screen length [L]
- n_e is effective porosity (specific yield) of the filter pack [dimensionless]
- r_c is nominal casing radius [L]
- r_w is effective well radius [L]

- R_e is external or effective radius of the test [L]
- t is elapsed time since initiation of the test [T] (*Bouwer and Rice Slug Test Solution for Unconfined Aquifers*, n.d.)

For the Mill Rd far piezometer that displayed an underdamped response, the Springer-Gelhar (1991) equation was used for analysis of the results. This method is used for slug tests in unconfined high-hydraulic conductivity aquifers and accounts for the inertial effects in the well and the oscillatory response, as well as frictional well loss in small-diameter wells (*Springer and Gelhar Slug Test Solution for Unconfined Aquifers*, n.d.). The solution involves fitting a type-curve to the slug test data set. This model has the same assumptions as outlined above for the Bouwer and Rice (1976) solution, except that it can only be used for unconfined aquifers (*Springer and Gelhar Slug Test Solution for Unconfined Aquifers*, n.d.). The Springer-Gelhar solution uses the following equation:

$$\frac{d^2w}{dt^2} + \frac{g}{L_e} w = \frac{g}{L_e}(h_0 - h_s) \quad (5)$$

where w [L] is drawdown at the surface of the water column; t [T] is time; g [L/T^2] is gravitational acceleration; L_e [L] is effective well length; and h_0-h_s [L] is the relation between drawdown at the well screen.

The K values obtained from the analysis are presented below in Table 4.5.

Table 4.5. Hydraulic conductivity (*K*) values obtained from slug testing of mini-piezometers

Well ID	Hydraulic Conductivity *K* (m/d)
Sheates Close Piezo	77
Sheates Far Piezo	52
Ollivers Close Piezo	12
Ollivers Far Piezo	28
Mill Close Piezo	5
Mill Far Piezo	148
Blacks Close Piezo	32
Blacks Far Piezo	20

Note: *K* values are averages of all slug tests performed on each well.

Figure 4.7 shows an example of slug test data analysis in AQTESOLV for the Ollivers Rd far piezometer using the Bouwer-Rice (1976) equation. The plot shows the head displacement in the well over time after the slug has been removed. A line is manually fit over the points that fall in the recommended head range and the program calculates the hydraulic conductivity based on the position of the line.

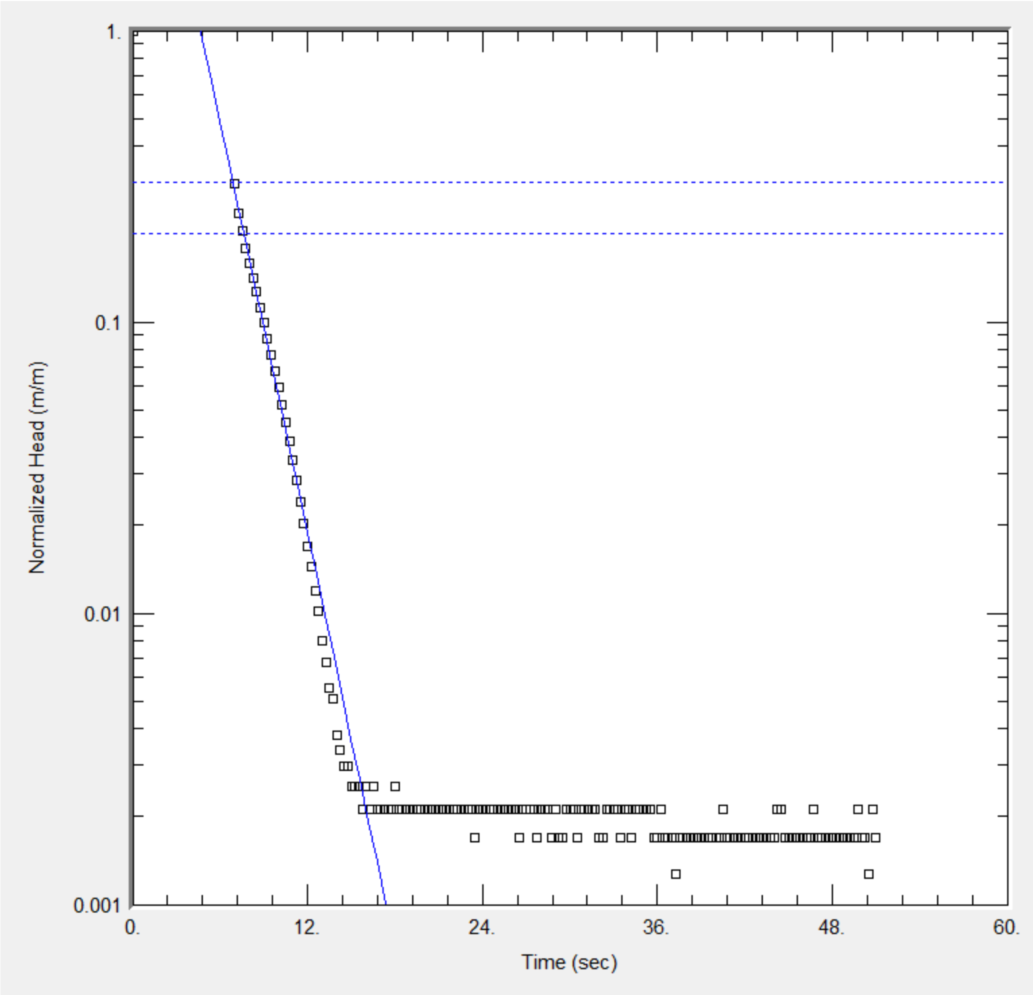


Figure 4.7. Screenshot of AQTESOLV analysis of slug test data from the Ollivers Rd far piezometer.

4.4 Diurnal temperature signal analysis

4.4.1 Summary

As discussed in section 3.3, vertical temperature probes were used at the study sites to measure vertical temperature exchange between surface water and groundwater in the streambed. Four iButton temperature sensors (model 1922L, ±0.5°C accuracy, 0.0625°C resolution) were placed in each of the four temperature probes at 5-cm spacing. The probes were installed into the river at the edges—one probe on each side of the river at the two sites. The temperature sensors were placed into the streambed at depths of 1, 6, 11 and 16 cm. Once installed in the river, the iButtons took readings at 10-minute intervals. Three sampling runs were completed in 2017: 4-11 July, 29 Aug-15 Sept, and 4-26 Oct.

After each sampling run, the iButtons were removed from the temperature probes and the data was transferred to a computer via a USB reader. The raw data was processed in a MATLAB-based script called VFLUX2 (v. 2.0.0) (Gordon et al., 2012; Irvine et al., 2015). VFLUX was developed by Gordon et al. (2012) to automate the processing of large temperature datasets and calculate the vertical flow of water in shallow sub-surface aquifers. This program identifies the direction of seepage through the streambed and calculates the vertical flux of water where the temperature probes are located. The flux value (also known as the Darcy velocity) is an estimate of the quantity of water flowing upwards or downwards through the streambed.

The fundamental equation behind the mathematical solutions used in VFLUX is the one-dimensional heat transport equation:

$$\frac{\delta T}{\delta t} = K_e \frac{\delta^2 T}{\delta z^2} - q \frac{C_w}{C} \frac{\delta T}{\delta z} \tag{6}$$

where T is temperature [°C], t is time [s], K_e is the effective thermal diffusivity of the saturated sediment [m^2/s], z is depth [m], q is fluid flux [m/s], C is the volumetric heat capacity of the saturated sediment [J/m^3/°C], and C_w is the volumetric heat capacity of the water [J/m^3/°C] (Gordon et al., 2012; Goto et al., 2005; Stallman, 1965). Positive flux values indicate downwelling whereas negative flux values indicate upwelling.

VFLUX first resamples the raw temperature time series at a lower sampling rate to extract the diurnal sinusoidal signal, and phase angle and amplitude information for each sensor using Dynamic Harmonic Regression programs from the Captain Toolbox (Young et al., 1999; Young et al., 2010). The program then uses temperature readings from different combinations of sensors in the filtered dataset to determine vertical flux at specific times and depths (Gordon et al., 2012) using heat transport models by Hatch et al. (2006), Keery et al. (2007), McCallum et al. (2012) and Luce et al. (2013). The data analysis in this thesis used an updated version of VFLUX (version 2.0.0, referred to as VFLUX2), published by Irvine et al. (2015).

Surface water bodies have a diurnal temperature cycle whereby they warm during the day and cool at night, producing a quasi-sinusoidal temperature signal with a 24-hour period (Gordon et al., 2012). This signal propagates through the streambed with varying speed, depth and magnitude depending on thermal properties of the sediment and water as well as the volume of the fluid (Gordon et al., 2012). VFLUX uses several solutions for one-dimensional heat transport as mentioned above, which use the amplitude ratio (A_r) and phase shift ($\Delta\phi$) to calculate the vertical flux (Figures 4.8-4.9). The McCallum et al. (2012) and Luce et al. (2013) equations also calculate thermal diffusivity, and in the case of the latter, sensor spacing, which can be used to determine if there has been streambed scour around the sensors (Gordon, 2015). The Hatch (2006) method that calculates flux based on the amplitude ratio has been used in this analysis. While there are other methods to calculate flux as described here, these can be prone to errors, such as the combined amplitude and phase shift methods, which need both a clear amplitude and phase shift, which is typically not the case. Also, methods using phase shift only cannot determine the direction of flux. Thus the Hatch (2006) method is the most widely used method, however a drawback is the need to use thermal conductivity of the substrate as an input, which can only be approximated (Irvine et al., 2017).

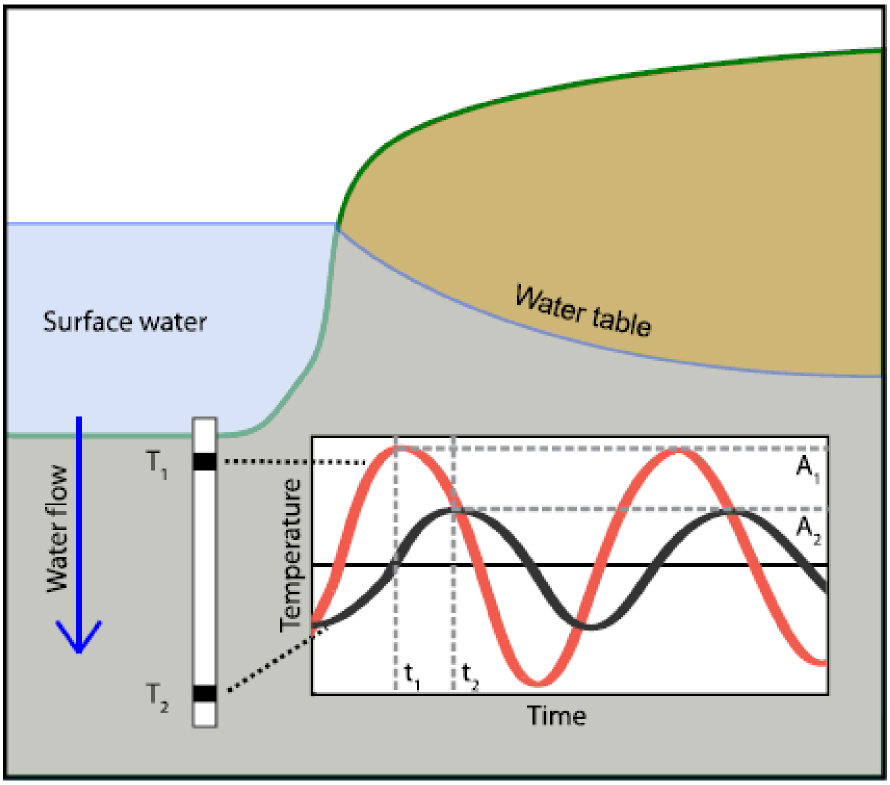


Figure 4.8. Conceptual diagram of temperature sensors installed to two different depths in a riverbed. The amplitude ratio and phase shift methods are illustrated here by showing the two temperature time series. The temperature signal is dampened and time lagged as it moves downward. Source: McCallum et al. (2012)

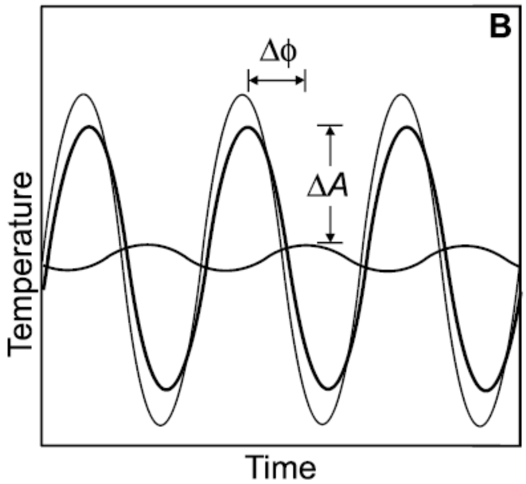


Figure 4.9. An example of diurnal signal patterns from three temperature sensor datasets. The amplitude ratios (A_r) and phase shifts ($\Delta\phi$) of these signals can be analysed to calculate seepage flux. Source: Hatch et al. (2006)

The Hatch (2006) method for calculating flux using the amplitude ratio (q_{Ar}) involves the following equation:

$$q_{A_r} = \frac{C}{C_w}\left(\frac{2k_e}{\Delta_z} lnA_r + \sqrt{\frac{\alpha + v_t^2}{2}}\right) \quad (7)$$

where C and C_w are the volumetric heat capacities of the saturated medium and water, respectively [J/m^3/°C]; k_e is the thermal diffusivity of the saturated medium [m^2/s]; z is the depth [m]; A_r is the amplitude ratio [dimensionless]; v_t is the thermal front velocity [m/s]; and $\alpha = \sqrt{v_t^4 + (8\pi k_e/P)^2}$, where P is the period of the temperature signal (i.e., 1 day). This method assumes one-dimensional flow, whereby it extracts the vertical component of flow from the multi-dimensional flow system.

The following thermal parameter inputs were used to run the VFLUX analysis:

- Porosity = 0.3 [dimensionless]
- Volumetric heat capacity of the sediment* = 2.12 x 10^6 [J/m^3/°C]
- Volumetric heat capacity of water = 4.184 X 10^6 [J/m^3/°C]
- Thermal conductivity of the sediment* = 3.00 [W/m/°C]
- Thermal conductivity of water = 0.6 [W/m/°C]

*Thermal properties of quartz were used for the sediment.

A sudden change in river flow levels can cause errors in the flux rate calculations and show a change in flux direction (Rau et al., 2010). Given this, it is very useful to collect concurrent stream flow data during measurements of temperature time series. The flow levels at the three flow recorder sites upstream of the study sites are plotted in Appendix C to aid in the interpretation of the flux results.

4.4.2 Sheates Road/Ollivers Road Transect

The following sections present results from temperature probes on the Sheates Rd/Ollivers Rd transect. Temperatures probes were installed in the right and left sides of the riverbed and are referred to as the Sheates and Ollivers probes, respectively. Flux directions and rates for each probe and sampling run are provided in Table 4.6. Flux results have been given “good” or “poor” ratings based on the size of the amplitude ratio (A_r). As discussed in the previous section, the Hatch (2006) analysis method calculates the flux rate based on the ratio of amplitude in the waves for specific temperature sensor pairs. Where A_r approaches 1, the flux cannot be calculated.

Table 4.6. Temperature probe results for the Sheates Rd/Ollivers Rd transect

Probe	**Dates**	**Reliable Flux?**	**Flux Direction**	**Flux (m/day)***	**Comment on reliability**
Ollivers	4-11 July	Poor	Downwelling	0.864 to 2.592	A_r** too close to 1
Ollivers	29 Aug-15 Sept	Good	Downwelling	0.216	
Ollivers	4-26 Oct	Good	Downwelling	0.086 to 0.604	
Sheates	4-11 July	Poor	Downwelling	0.432 to 0.864	A_r too close to 1
Sheates	29 Aug-15 Sept	Good	Upwelling	-1.728 to -1.555	
Sheates	4-26 Oct	Good	Upwelling	-.432	

*Positive values = downwelling; negative values = upwelling; **A_r = amplitude ratio

Figure 4.10 shows the raw temperature dataset for the Sheates Road probe during 29 Aug-15 September as an example of how this bulk data looks before it is processed in VFLUX. There is a large number of temperature readings in this data set (n=2,213), so there is a lot of noise in the plot, however even here the diurnal cycle of temperature at different depths is clear beginning on the third day of sampling.

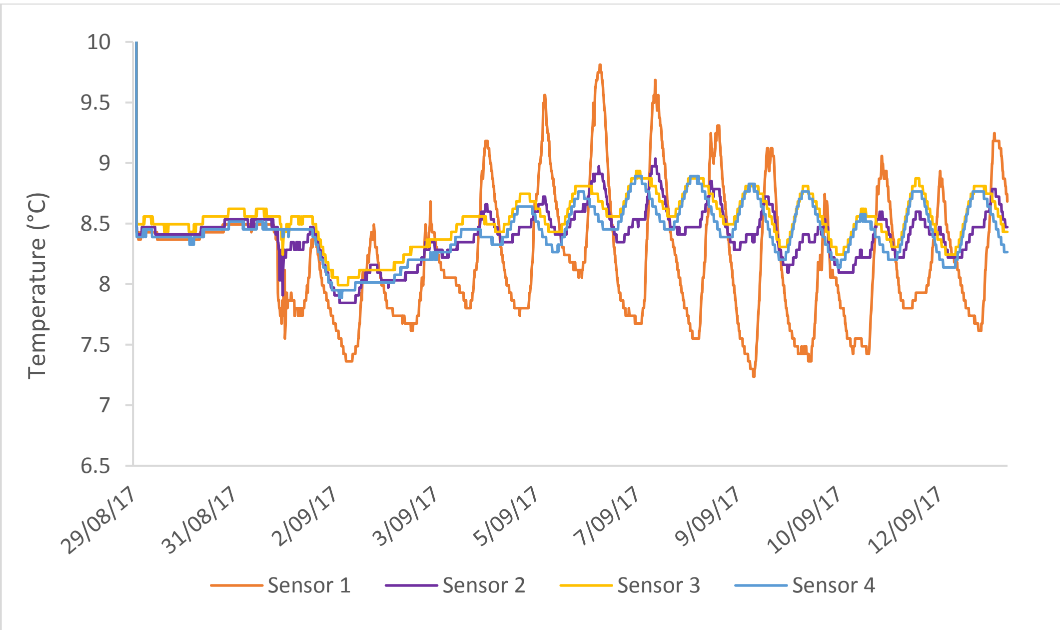


Figure 4.10. Raw temperature dataset for 29 Aug-15 Sept 2017 for the Sheates Road temperature probe. Sensor depths: (1) = 1 cm, (2) = 6 cm, (3) = 11 cm, (4) = 16 cm.

The following sections includes plots of the filtered temperature and flux rates for data sets that were deemed reliable (as discussed above).

4.4.2.1 Sheates Road Probe

Figure 4.11. Filtered temperature dataset for 29 Aug-15 Sept 2017 for the Sheates Road temperature probe.

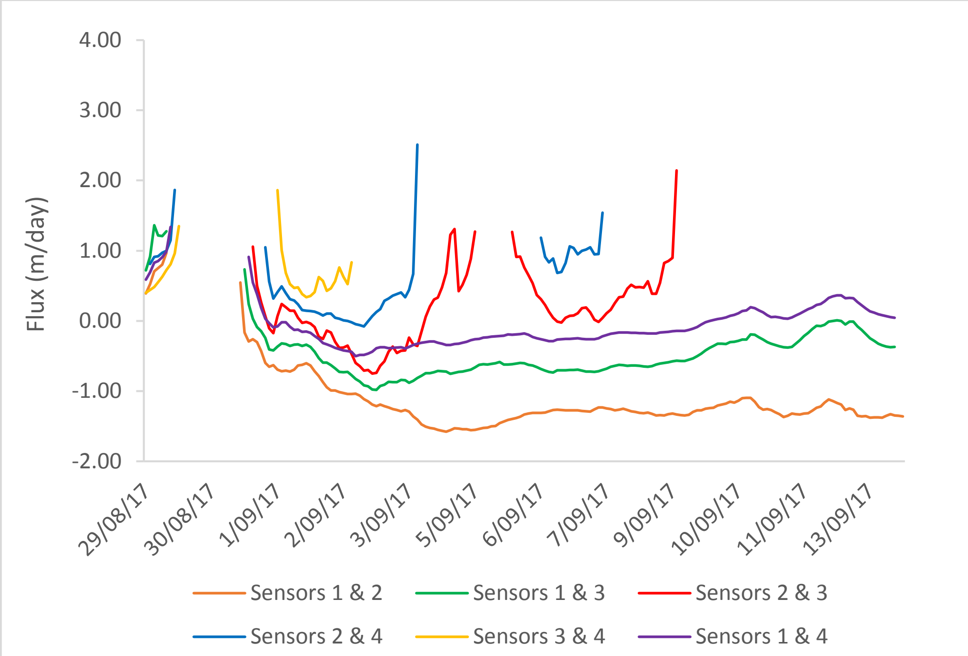


Figure 4.12. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Sheates Road temperature probe during 29 Aug-15 Sept 2017. Positive values = downwelling; Negative values = upwelling.

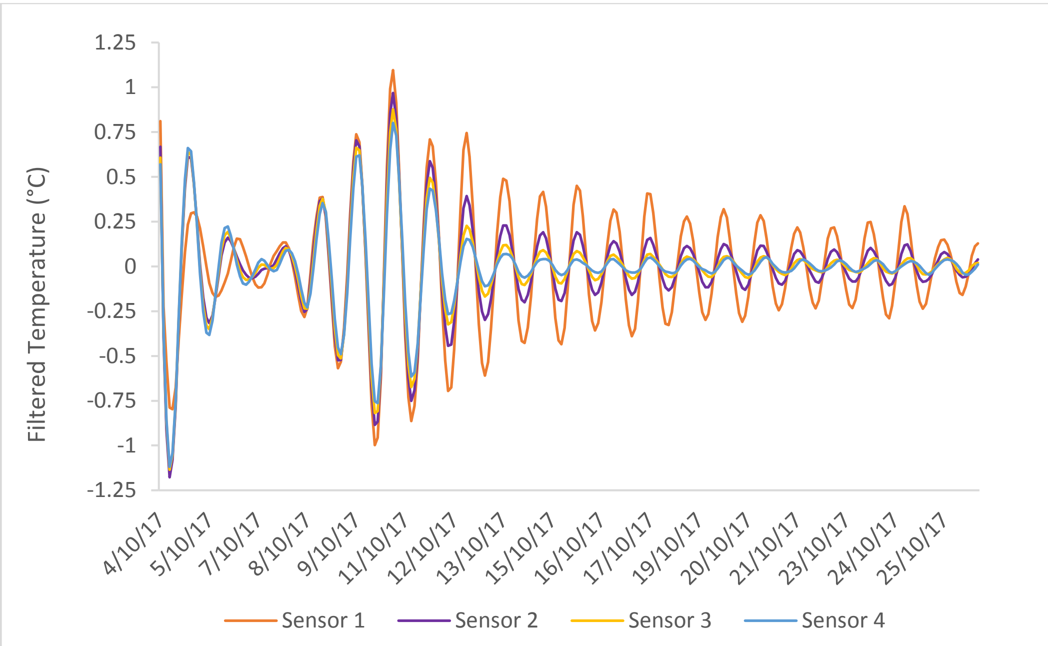


Figure 4.13. Filtered temperature dataset for 4-26 Oct 2017 for the Sheates Road temperature probe.

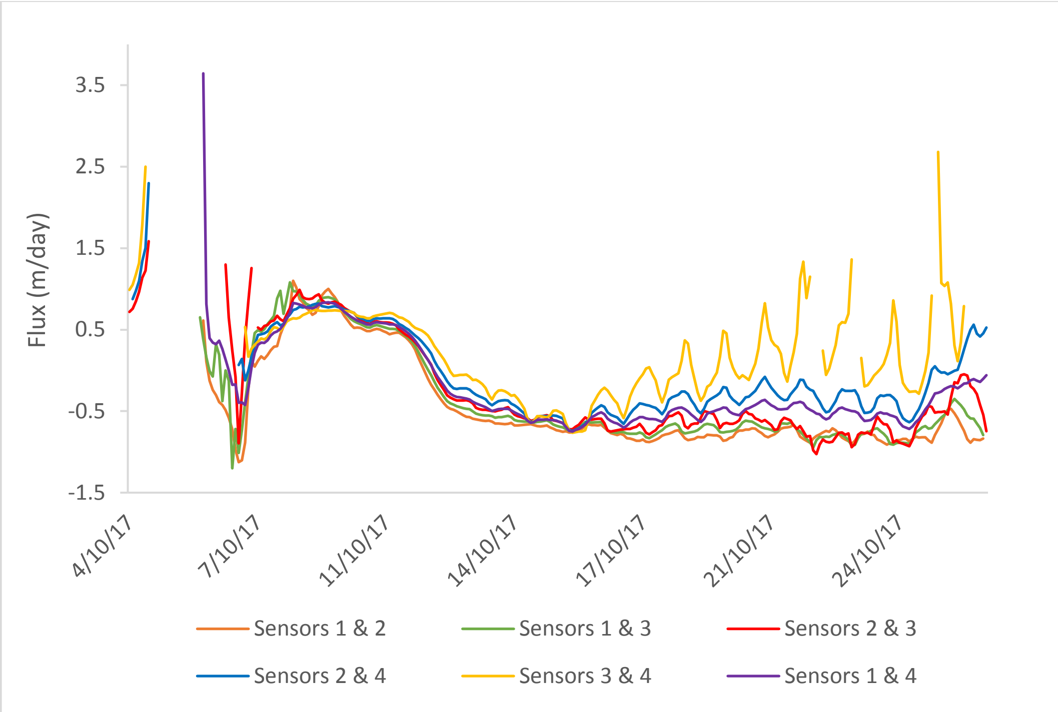


Figure 4.14. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Sheates Road temperature probe during 4-26 Oct 2017. Positive values = downwelling; Negative values = upwelling.

4.4.2.2 Ollivers Road Probe

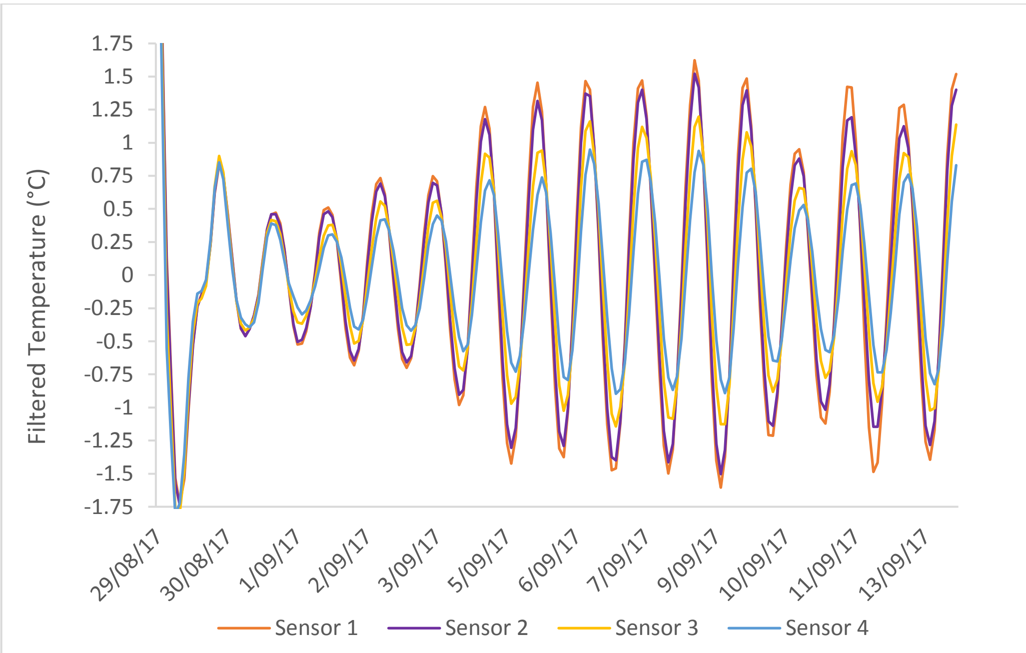


Figure 4.15. Filtered temperature dataset for 29 Aug-15 Sept 2017 for the Ollivers Road temperature probe.

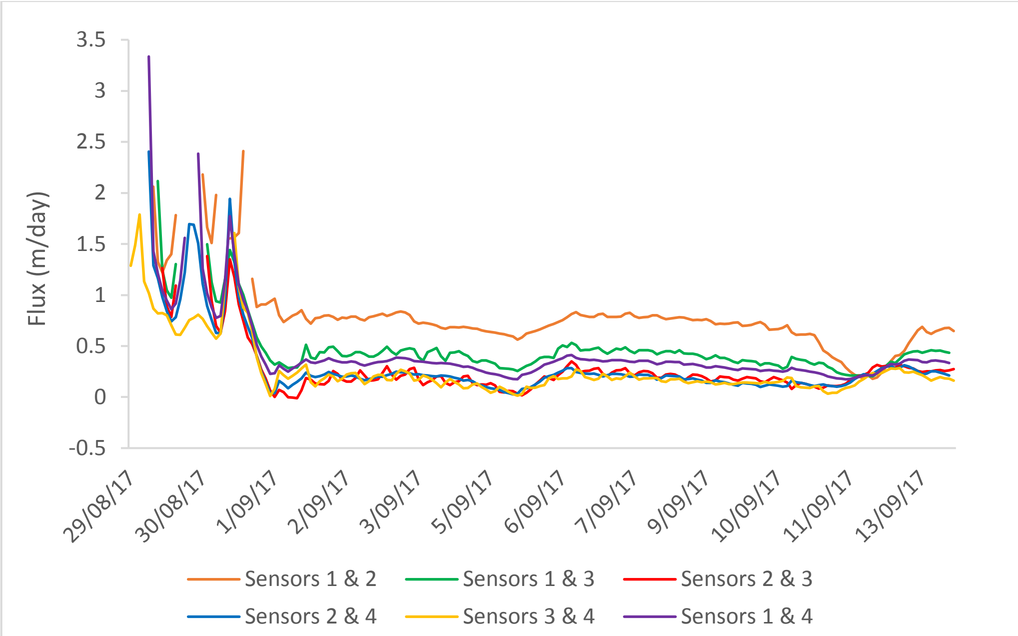


Figure 4.16. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Ollivers Road temperature probe during 29 Aug-15 Sept 2017. Positive values = downwelling; Negative values = upwelling.

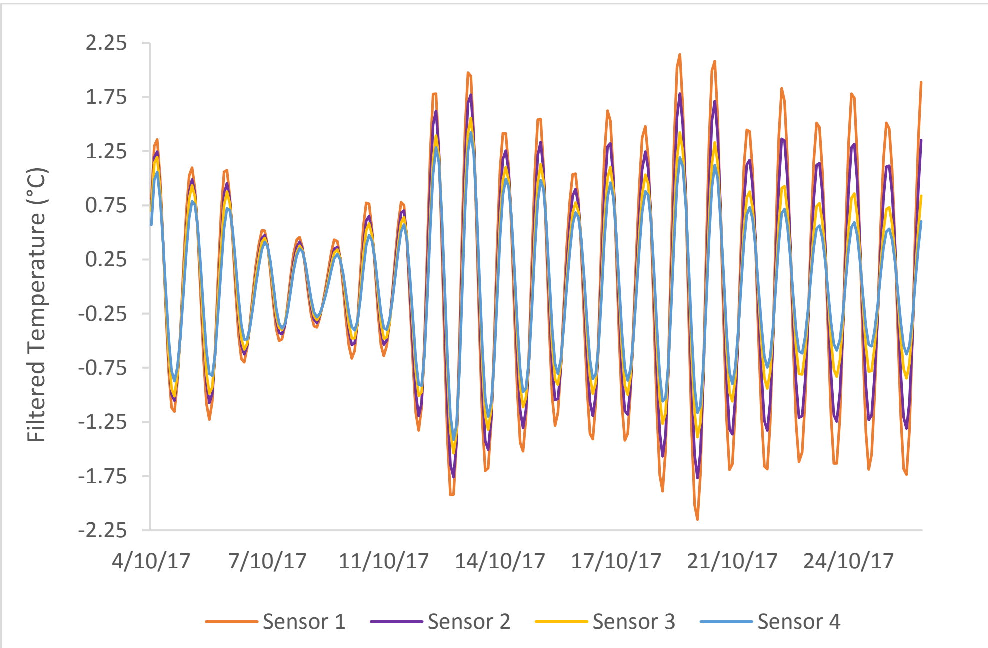


Figure 4.17. Filtered temperature dataset for 4-26 Oct 2017 for the Ollivers Road temperature probe.

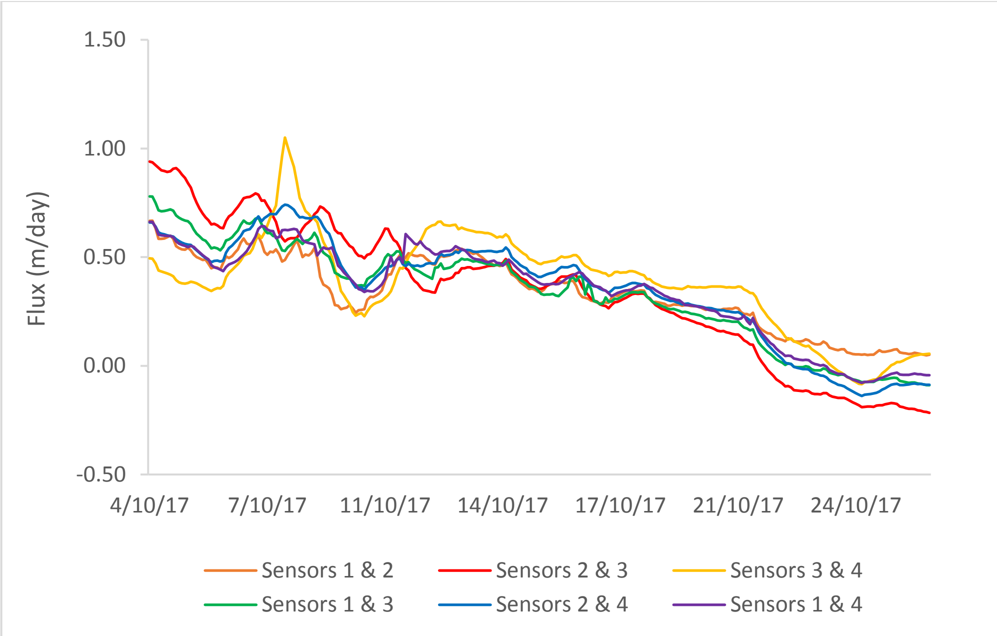


Figure 4.18. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Ollivers Road temperature probe during 4-26 Oct 2017. Positive values = downwelling; Negative values = upwelling.

4.4.3 Mill Road/Blacks Road Transect

The following sections present results from temperature probes on the Mill Rd/Blacks Rd transect. Temperatures probes were installed in the right and left sides of the riverbed and are referred to as the Mill and Blacks probes, respectively. Flux directions and rates for each probe and sampling run are provided in Table 4.7. As described above, the flux rate reliability has been rated based on the size of the amplitude ratio (A_r). The following sections include plots of the filtered temperature and flux rates for data sets that were deemed reliable.

Table 4.7. Temperature probe results for the Mill Rd/Blacks Rd transect

Probe	**Dates**	**Reliable Flux?**	**Flux Direction**	**Flux (m/day)***	**Comment on reliability**
Blacks	4-11 July	Good	Upwelling	-1.037 to -0.864	
Blacks	29 Aug-15 Sept	Good	Downwelling	0.259	
Blacks	4-26 Oct	Good	Downwelling	2.592	
Mill	4-11 July	Poor	Downwelling	0.864 to 1.296	A_r** too close to 1
Mill	5 Sept-15 Sept	Good	Downwelling	0.864	
Mill	4-26 Oct	Poor	Downwelling	0.864 to 1.728	A_r too close to 1

*Positive values = downwelling; negative values = upwelling; **A_r = amplitude ratio

4.4.3.1 Mill Road Probe

It is important to note that the second sampling run for this probe was delayed to Sept 5th due to issues with private property access.

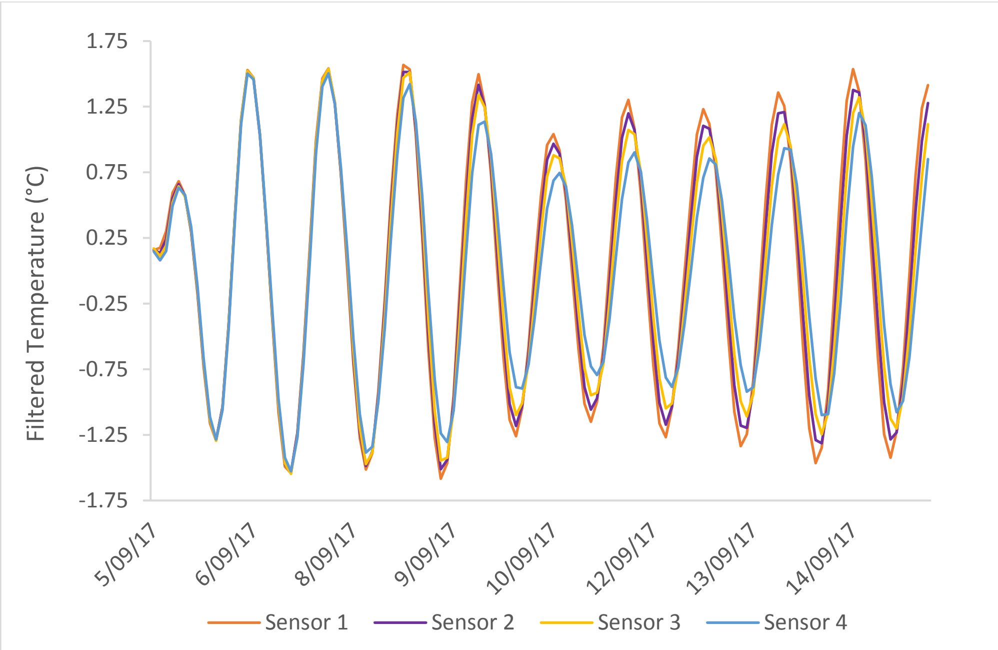


Figure 4.19. Filtered temperature dataset for 5-15 Sept 2017 for the Mill Road temperature probe.

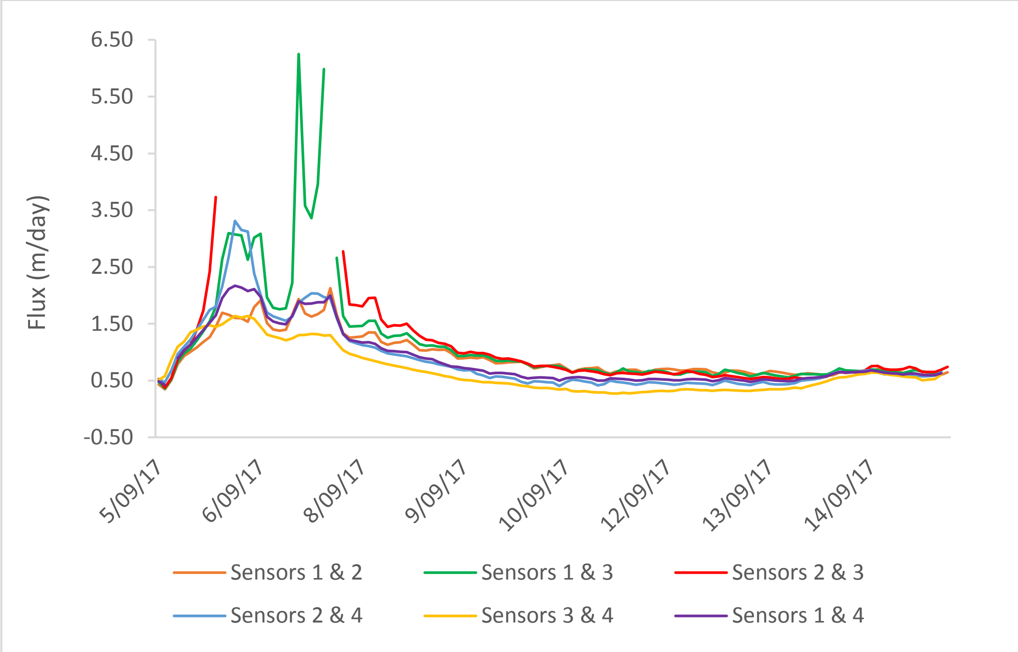


Figure 4.20. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Mill Road temperature probe during 5-15 Sept 2017. Positive values = downwelling; Negative values = upwelling.

4.4.3.2 Blacks Road Probe

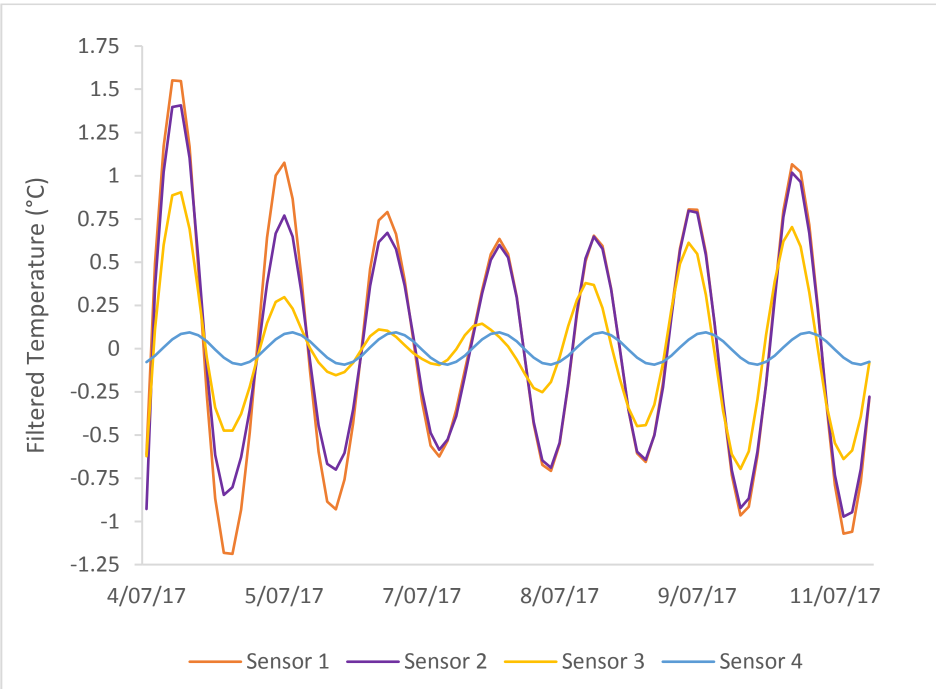


Figure 4.21. Filtered temperature dataset for 4-11 July 2017 for the Blacks Road temperature probe.

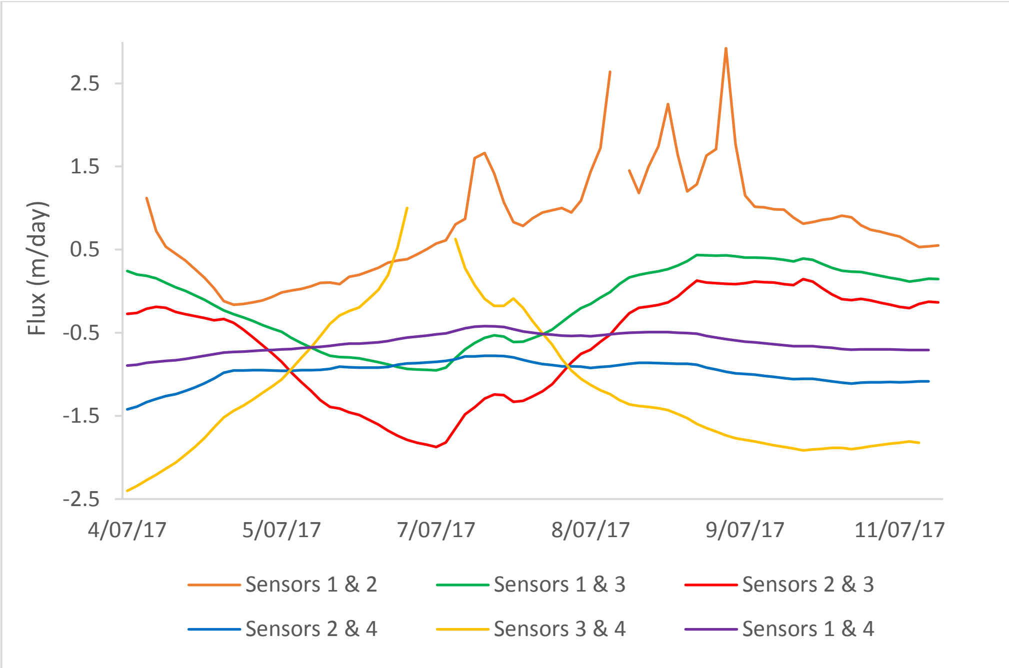


Figure 4.22. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Blacks Road temperature probe during 4-11 July 2017. Positive values = downwelling; Negative values = upwelling.

Figure 4.23. Filtered temperature dataset for 29 Aug-15 Sept 2017 for the Blacks Road temperature probe.

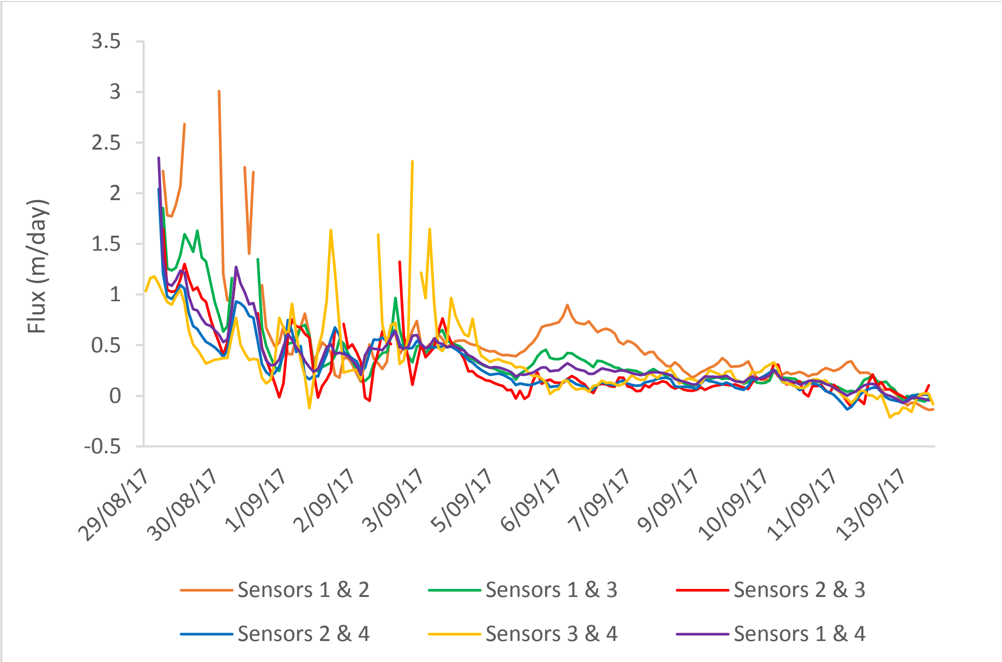


Figure 4.24. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Blacks Road temperature probe during 29 Aug-15 Sept 2017. Positive values = downwelling; Negative values = upwelling.

Figure 4.25. Filtered temperature dataset for 4-26 Oct 2017 for the Blacks Road temperature probe.

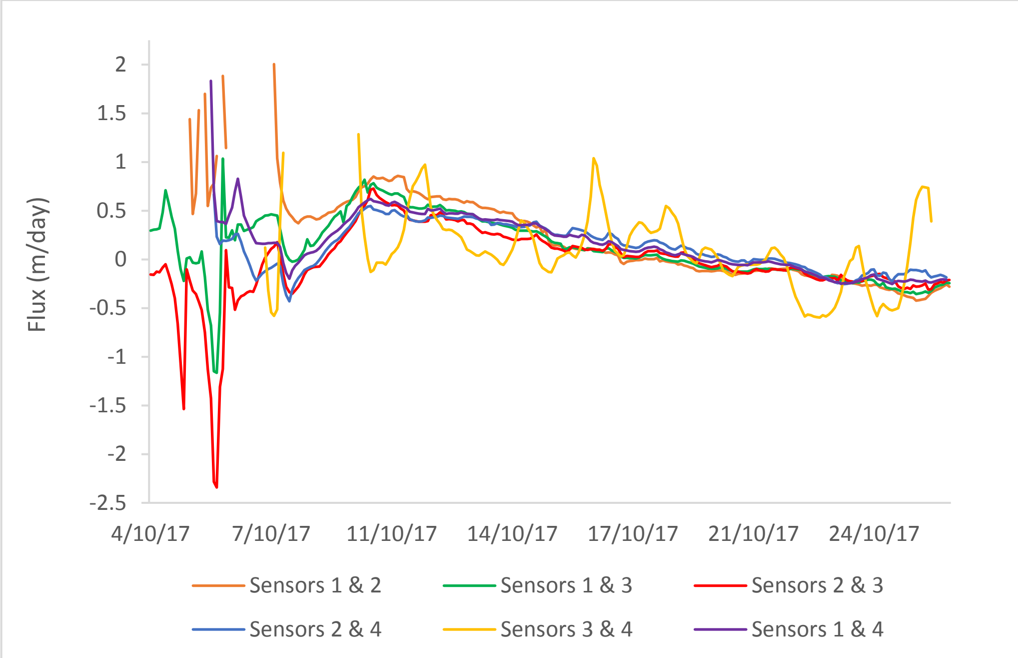


Figure 4.26. Flux values for various combinations of temperature sensors using the Hatch equation (2006) for the Blacks Road temperature probe during 4-26 Oct 2017. Positive values = downwelling; Negative values = upwelling.

4.5 Physicochemical sampling

As discussed in sections 3.2.1.5 and 3.2.2.3, physical and chemical sampling was carried out on the well transects on three occasions: 26-27 Sept, 11-13 Oct and 17-18 Oct 2017. Temperature, conductivity, pH, nitrate-nitrogen and dissolved reactive phosphorus were measured in each of the wells, and the results are presented in the following sections for each well transect. The full results are provided in tables and individual parameters are plotted in sections 4.5.1 and 4.5.2. The plots of individual parameters show averaged values across the three sampling periods. It is worth noting that the temperatures probes did not fit down wells K37/2382 and K37/0133, so no direct temperature measurements were taken at these locations. Also, it is important to distinguish the different temperature measurement method used here from the diurnal temperature signal analysis. As part of the physicochemical sampling, temperature measurements were taken at one point in time in the river and wells, as opposed to the temperature time series data collected with the iButtons.

There are concerns about the accuracy of the DRP results, and for this reason they have not been included in this thesis to avoid use of this data in future work where the limitations might not be noted. Median DRP values for the river and groundwater were an order of magnitude higher than the median value obtained in Environment Canterbury's 2016 regional groundwater survey (Hanson, 2017) and DRP readings obtained on the HACH colorimeter were highly variable. There are a few general explanations for this apparent issue if the readings are considered incorrect: phosphate contamination during sampling and analysis may have given artificially high readings; there may have been an issue with the reagent or colorimeter used in the analysis; or there may be an error in the Environment Canterbury values. Regarding potential contamination, this is a reasonable explanation given the tendency of phosphorus to stick to certain materials and result in cross-contamination of samples, either from sample water or phosphate-based detergents. There was some equipment that was used for multiple sampling instances that came in contact with sample water, such as the plastic tubing used to pump out wells; plastic buckets and containers used to collect samples; syringes used to fill sample vials; and the glass sample vials. All sampling equipment was rinsed with either sample water (of a new sample) or deionised water before a new sample was analysed, and all samples were filtered. To the author's knowledge, no phosphate-based detergents were used to clean the sampling equipment during the sampling program. Given the high readings occurred across all three sampling runs in both groundwater and surface water samples, if contamination were the cause of the issue, it would have needed to affect the entire sampling program. In terms of issues with the colorimeter, the instrument was calibrated before the sampling began and was tested after sampling by the Waterways Centre Laboratory Technician once issues were reported. The Laboratory Technician tested the colorimeter against several standards, and reported that the instrument appeared to be working as expected. Some of the powder pillow reagent was also tested to determine if this was the source of the issue. Reagent from one manufacturing batch was tested and gave very high false and variable readings. The issue was thought to be isolated to this batch, however the sampling program here used reagent from multiple manufacturing batches. It is worth noting the HACH portable colorimeters have been used extensively for water quality testing at the Waterways Centre without any reported issues and have been tested in depth for accuracy.

4.5.1 Sheates Road/Ollivers Road Transect

Table 4.8. Sampling results from the Sheates Road/Ollivers Road well transect

Sampling Location	Date	Temperature (°C)	pH	Conductivity (µS/cm)	NO^3-N Mean (mg/L)	NO^3-N Min (mg/L)	NO^3-N Max (mg/L)
River @ Sheates Rd	26-27 Sept	9.1	7.22	59.08	0.8	0.7	0.9
Sheates Close Piezo	26-27 Sept	9.2	6.27	115.30	0.4	0.4	0.5
Sheates Far Piezo	26-27 Sept	10.1	6.75	118.20	1.8	1.6	1.9
K37/2382	26-27 Sept	**	6.31	173.60	3.7	3.3	4.1
Ollivers Close Piezo	26-27 Sept	8.9	6.94	73.04	0.9	0.9	1.0
Ollivers Far Piezo	26-27 Sept	9.8	6.45	134.20	2.4	2.3	2.5
K37/0133	26-27 Sept	**	6.76	132.50	2.4	2.3	2.5
River @ Sheates Rd	11-13 Oct	10	6.82	68.60	0.7	0.6	0.7
Sheates Close Piezo	11-13 Oct	9.8	6.25	117.00	0.3	0.2	0.4
Sheates Far Piezo	11-13 Oct	10.4	6.07	115.10	1.2	1.1	1.4
K37/2382	11-13 Oct	**	6.26	185.70	3.5	3.2	3.8
River @ Ollivers Rd	11-13 Oct	13.6	6.77	79.15	0.7	0.6	0.9
Ollivers Close Piezo	11-13 Oct	10.4	6.82	76.99	0.8	0.7	0.9
Ollivers Far Piezo	11-13 Oct	11.2	6.52	128.30	1.9	1.8	2.0
K37/0133	11-13 Oct	**	6.91	122.70	1.6	1.6	1.7
River @ Sheates Rd	17-18 Oct	11.1	6.85	79.51	0.8	0.7	0.8
Sheates Close Piezo	17-18 Oct	10.0	6.46	111.60	0.5	0.4	0.5
Sheates Far Piezo	17-18 Oct	10.8	6.50	114.20	1.1	1.0	1.2
K37/2382	17-18 Oct	**	6.17	197.80	3.5	3.2	3.6
Ollivers Close Piezo	17-18 Oct	10.2	6.98	82.01	0.7	0.6	0.8
Ollivers Far Piezo	17-18 Oct	10.4	6.47	135.10	1.3	1.2	1.4
K37/0133	17-18 Oct	**	7.00	123.50	1.4	1.4	1.4
Average		10.3	6.60	115.60	1.5		
Min		8.9	6.07	59.08		0.2	
Max		13.6	7.22	197.80			4.1

Note: NO^3-N = nitrate-nitrogen; **No temperature readings where measurements could not be made directly in wells.

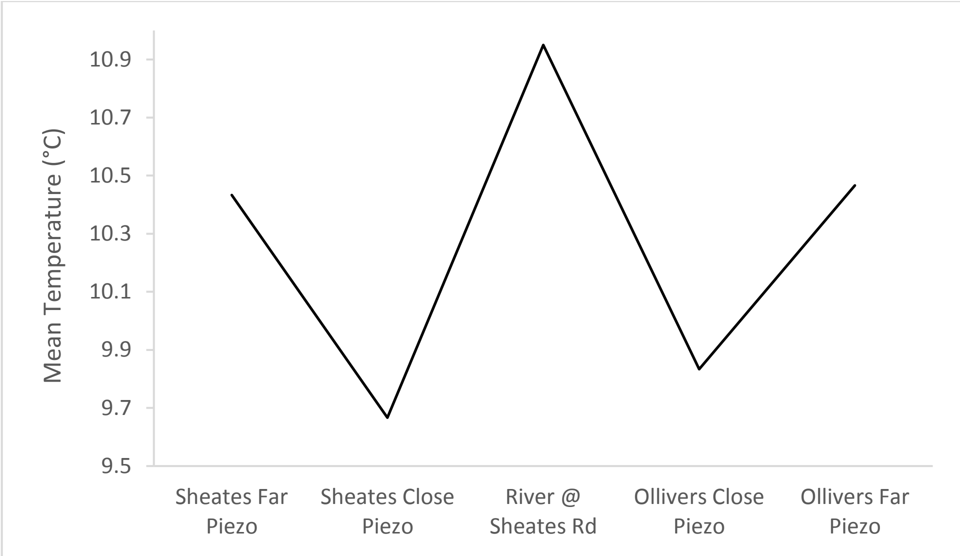


Figure 4.27. Average temperature readings on the Sheates Road/Ollivers Road transect (arranged south to north). Temperature in groundwater wells K37/2382 and K37/0133 could not be measured directly and thus are not included.

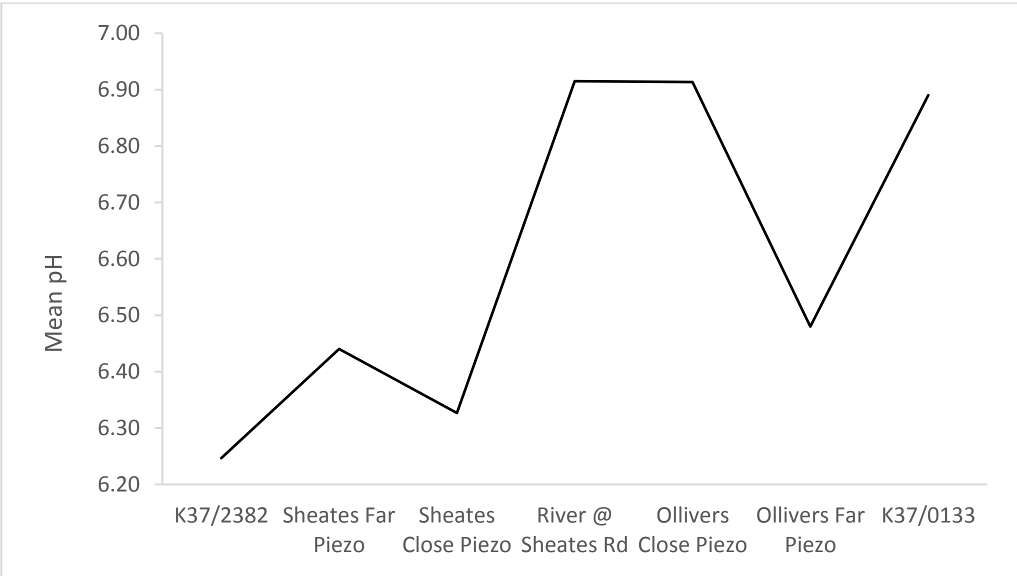


Figure 4.28. Average pH readings on the Sheates Road/Ollivers Road transect (arranged south to north).

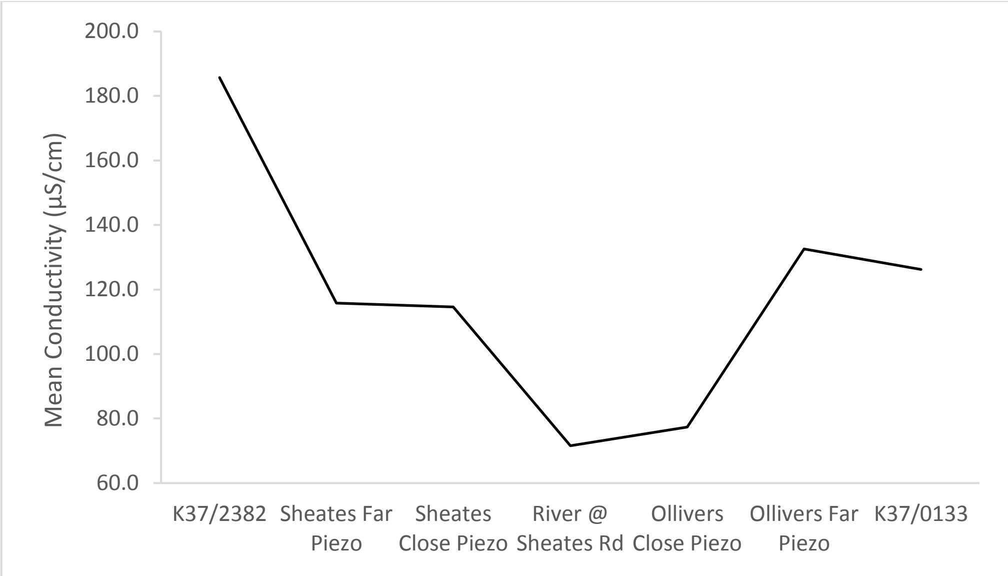


Figure 4.29. Average conductivity readings on the Sheates Road/Ollivers Road transect (arranged south to north).

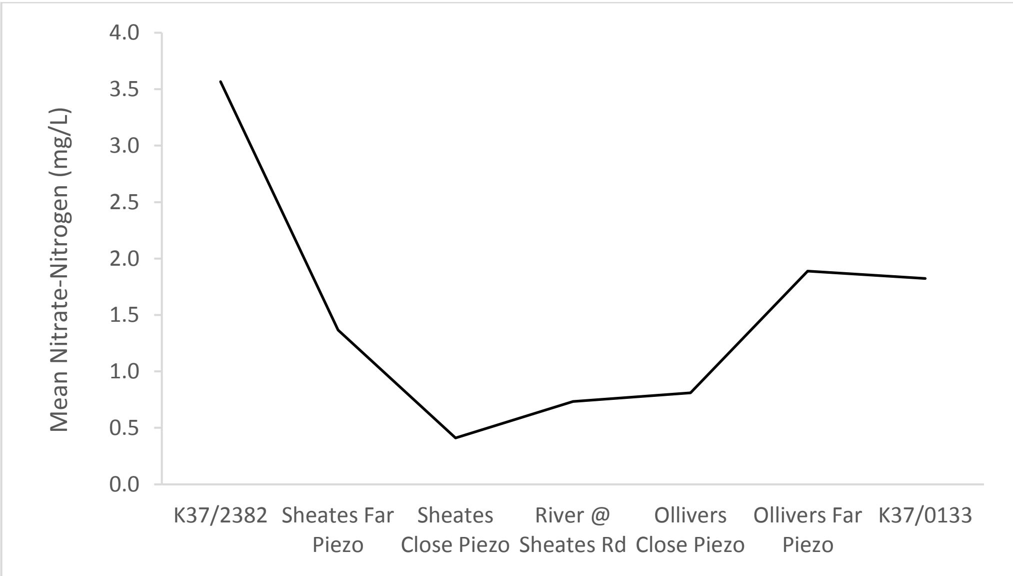


Figure 4.30. Average nitrate-nitrogen (NO^3-N) readings on the Sheates Road/Ollivers Road transect (arranged south to north).

4.5.2 Mill Road/Blacks Road Transect

Table 4.9. Sampling results from the Mill Road/Blacks Road well transect

Sampling Location	Date	Temperature (°C)	pH	Conductivity (µS/cm)	NO^3-N Mean (mg/L)	NO^3-N Min (mg/L)	NO^3-N Max (mg/L)
Mill Close Piezo	26-27 Sept	10.7	7.50	85.80	1.5	1.5	1.5
River @ Mill Rd	26-27 Sept	10.9	7.08	75.70	1.0	0.9	1.1
Mill Far Piezo	26-27 Sept	11.1	6.71	224.00	4.6	4.6	4.7
K37/3091	26-27 Sept	10.0	6.57	422.70	18.3	15.9	21.5
Blacks Close Piezo	26-27 Sept	9.6	6.90	82.02	1.3	1.3	1.4
Blacks Far Piezo	26-27 Sept	**	6.20	132.40	4.2	4.1	4.3
Mill Close Piezo	11-13 Oct	11.2	6.95	80.32	0.7	0.3	0.9
River @ Mill Rd	11-13 Oct	11.8	7.86	87.53	1.2	1.1	1.2
Mill Far Piezo	11-13 Oct	10.9	6.39	218.60	3.3	3.1	3.4
K37/3091	11-13 Oct	**	6.85	425.80	16.1	14.3	17.1
Blacks Close Piezo	11-13 Oct	10.4	6.72	116.20	0.8	0.8	0.8
Blacks Far Piezo	11-13 Oct	11.2	6.39	183.50	3.4	3.3	3.6
Mill Close Piezo	17-18 Oct	12.0	7.06	84.69	1.0	0.9	1.2
River @ Mill Rd	17-18 Oct	10.6	6.88	93.07	1.1	1.1	1.2
Mill Far Piezo	17-18 Oct	10.8	6.50	219.50	3.9	3.4	4.1
K37/3091	17-18 Oct	10.3	6.87	430.00	10.1	9.0	11.6
Blacks Close Piezo	17-18 Oct	10.5	6.72	116.80	0.8	0.7	0.9
Blacks Far Piezo	17-18 Oct	11.5	6.30	185.10	3.4	3.3	3.5
Average		10.8	6.80	181.30	4.3		
Min		9.6	6.20	75.70		0.3	
Max		12.0	7.86	430.00			21.5

Note: NO^3-N = nitrate-nitrogen; **Unable to take temperature readings due to probe malfunction.

Figure 4.31. Average temperature readings on the Mill Road/Blacks Road transect (arranged south to north).

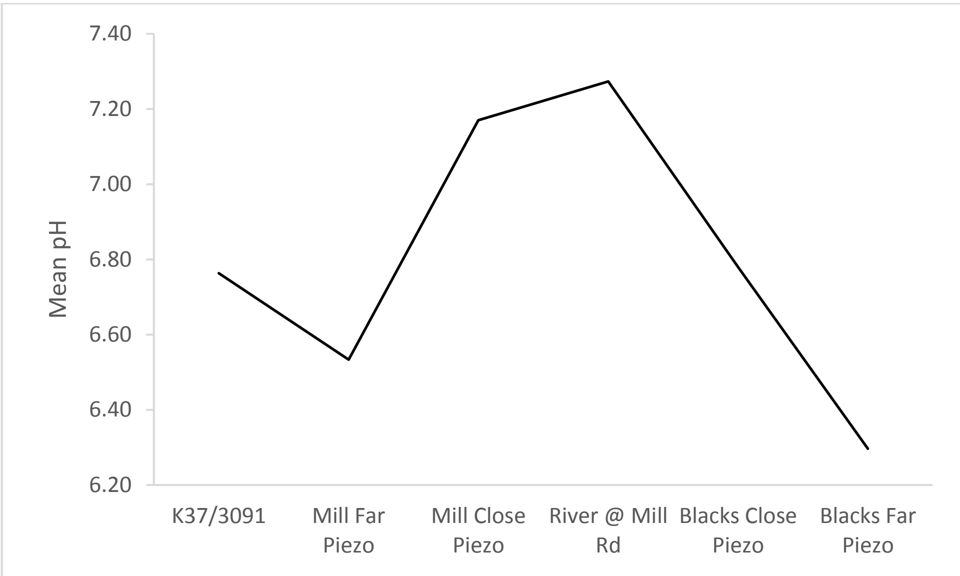


Figure 4.32. Average pH readings on the Mill Road/Blacks Road transect (arranged south to north).

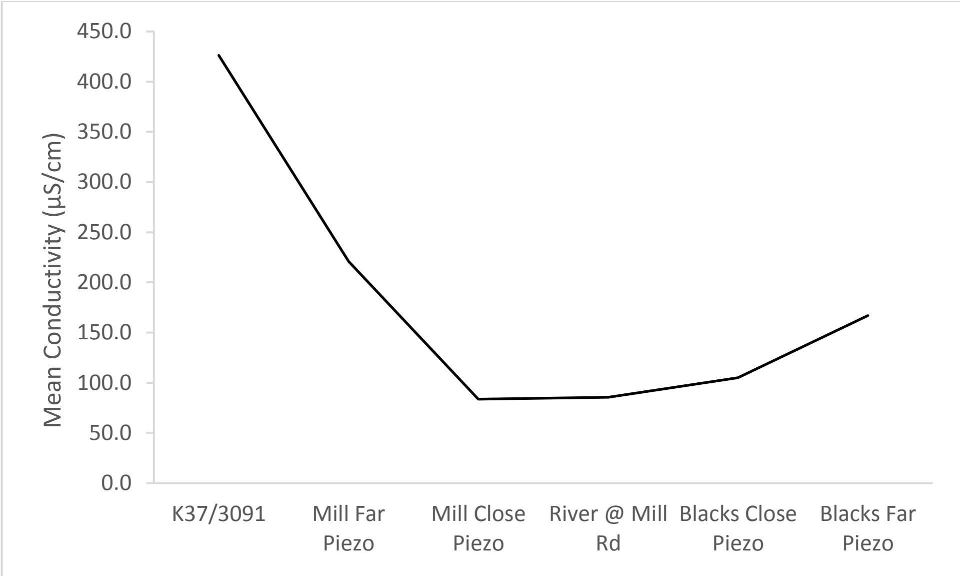


Figure 4.33. Average conductivity readings on the Mill Road/Blacks Road transect (arranged south to north).

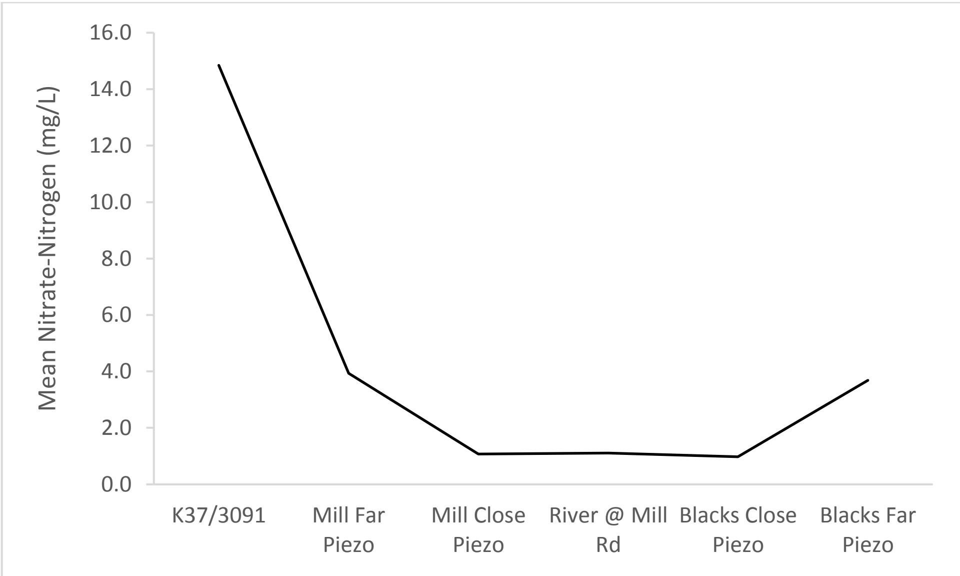


Figure 4.34. Average nitrate-nitrogen (NO^{3}-N) readings on the Mill Road/Blacks Road transect (arranged south to north).

4.6 Flow gauging

This research program was carried out during a period of high rainfall and snowfall. This resulted in river levels being too high to carry out flow gauging. In order for the gauging to effectively measure streambed seepage, the river needs to be at minimum flow levels so there is no influence of rainfall. Furthermore, based on results from this study and previous studies (such as Horrell (2001)), there is reason to believe that flow gauging along the small seepage runs as planned would not produce useful results. Based on estimations by Horrell (2001), there is a net gain of .177 m^3/s in the South Branch between Ollivers and Blacks Rd. With normal error margins associated with stream gauging, plus the increased error often seen in large rivers (Rosenberry & LaBaugh, 2008), it is very likely that the error margin of the gauging would far exceed the net seepage along these seepage runs.

4.7 Results presented to landowners

Access to private property and wells was essential for this study, so without the assistance of landowners, this work would not have been possible. Most of the landowners that were involved with this study are deeply interested in water quality issues and questions of groundwater flow paths near their properties. Given this, results relevant to the individual landowners have been prepared and presented to them. These results are included in Appendix D.

Chapter 5. Discussion

This chapter presents an overall discussion of the study's results and an evaluation of whether the thesis objectives were achieved. As this study is a comparison of methodologies for measuring groundwater-surface water interactions in braided rivers, the results from the methods are discussed individually and compared in detail. The effectiveness and limitations of the methods and overall study design are discussed, as well as potential for future research.

5.1 Scoping exercise

As discussed in section 3.2.1.2, a preliminary investigation was carried out to determine the boundary of surface water and groundwater in mini-piezometers installed on the margins of the river. Conductivity and pH were measured at four discrete intervals in each mini-piezometer at two sites: Ollivers Road and Blacks Road. These parameters were also measured in two nearby shallow groundwater wells: K36/0033 (about 850 m from Bowyers Stream, a tributary of the South Branch) and K36/0119, approximately 350 m north of the North Branch.

The intention was to compare the measurements taken in the wells with readings in the river adjacent to the mini-piezometers. It was anticipated that conductivity and temperature would be the most reliable indicators of either surface water or groundwater presence in this case, as they are often distinct in surface water and groundwater (Rosenberry & LaBaugh, 2008). Temperature changes in surface water seasonally and throughout the day, while groundwater beyond a certain depth generally does not fluctuate, so it is important to take this into consideration when attempting to compare temperatures in surface water and groundwater. Dissolved oxygen and pH can also be used as indicators of surface water and groundwater sources, but these may prove unreliable as they can vary spatially and temporally (J. Webster-Brown, personal communication, 8 June 2017). This scoping exercise was intended to use quick and simple techniques, so parameters that could be measured on site with probes were selected. Unfortunately, on the day of sampling a probe that could measure temperature directly in the wells was not available, so while temperature was measured while purging the wells, these measurements do not serve as accurate representations of groundwater temperature.

Overall, the results of this preliminary investigation were inconclusive. Conductivity measured in the wells was very similar to the river, while pH was not. Conductivity readings in the river at Ollivers Rd and Blacks Rd were 106.2 and 109.1 µS/cm, respectively. Conductivity readings in the mini-piezometer installed at Ollivers Rd ranged from 99.4-104.4 µS/cm, and at Blacks Rd they ranged from 102.2-102.9 µS/cm. The conductivity measurement in well K36/0119 was similar at 110.1 µS/cm, while well K36/0033 had a much higher reading at 454 µS/cm. For comparison, the median conductivity value in Environment Canterbury's 2016 regional groundwater water quality survey was 192 µS/cm (Hanson, 2017). There could be several reasons for the higher reading at K36/0033: this well was the deepest of all wells sampled at 8.23 m below ground, and it was the furthest from the river (~850 m from Bowyers Stream). The similarity of conductivity values in the other wells compared to the river suggests groundwater mixing with river water at these locations. Given the very close proximity of the piezometer installation from wet river channels (~1 m), the influence of surface water at these depths (a maximum of 2.08 m below ground) is not surprising.

There was a substantial difference in pH readings for the river and the wells. pH in the river was 8.0 at Ollivers and 7.98 at Blacks, while the values in the wells ranged from 6.19-6.89. For comparison, the median pH value recorded in the field in Environment Canterbury's 2016 regional groundwater water quality survey was 6.7 (Hanson, 2017). However, as noted above, pH can be an unreliable tracer of groundwater and surface water sources given its tendency to vary spatially and temporally.

5.2 Groundwater well observations

Mini-piezometers purpose built for this study and existing shallow wells were used to collect various types of data throughout the course of this thesis research. Water levels were measured, chemical analysis of the wells was conducted and slug tests were performed.

5.2.1 Piezometric surveys

Seven water level surveys were carried out during September-November 2017. This data has provided a general picture of shallow groundwater levels near the study sites and the direction of horizontal hydraulic gradient has been calculated. The hydraulic gradients are discussed in this section in terms of the direction that water is moving relative to the river (i.e. a water level in a groundwater well that is higher than the river is referred to as a negative gradient in this case).

Across the seven piezometric surveys, the range in measured groundwater levels was 0.326-2.742 m below the top of the well casing. For the mini-piezometers specifically, the range in levels was 0.326-2.133 m below the top of the well casing. In terms of water heights in metres above sea level, the range for all wells was 135.265-162.771 m.a.s.l. and for the mini-piezometers specifically, it was 136.925-156.177 m.a.s.l. Water levels in the mini-piezometers were generally very close to that of the river, which supports the results of Aitchison-Earl and Ritson (2013) who found that groundwater levels were higher near the river and deeper in the inland plains.

It is important to note that there is a ±33 mm error margin associated with the water level heights. This is due to a few factors. Firstly, as discussed in section 3.2.3, there was a ±18 mm vertical accuracy in the GPS coordinates measured in the differential GPS survey. Secondly, there are various possible errors associated with electric water level meters such as the Solinst 102M water meter used in this study. The cable can stretch over time, the metal weight on the end of the meter can cause the water level in the well to rise, the metal on the cable end may curve, or there may be human error in reading the measurements. These factors can result in artificially high or low readings. A US Geological Survey study

(Jelinski et al., 2014) tested the accuracy of a range of electric water level meters, including a model similar to the one used in this study. The study concluded the meters are in general accurate to ±15 mm.

On the Sheates Rd/Ollivers Rd transect, water levels from well K37/2382 north to the Ollivers Rd far piezometer were in general flat and showed at most a very small horizontal hydraulic gradient. The exception was well K37/0133 on the north end of the transect, where the water level was considerably higher (~7 m) than that of the rest of the transect, and there was a more discernible negative horizontal hydraulic gradient between this well and the rest of the transect. On the south side of the transect, there was a very minimal gradient (on average 10^{-4}-10^{-5}, fluctuating between a positive and negative direction) between well K37/2382 and the two Sheates Rd piezometers. There was a consistent small negative gradient (on average 10^{-3}) between the close piezometers on either side of the river and the piezometer in the river (i.e. showing water levels lower in the river than in the adjacent piezometers). Between the two Ollivers Rd piezometers, there was a slight positive gradient where there were consistently higher water levels in the close piezometer than the far piezometer. As mentioned, the more significant gradient was between the Ollivers far piezometer and well K37/0133. The negative gradient was approximately 10^{-2} between the two wells, with water levels higher in K37/0133, however it is important to note that water levels in K37/0133 could only be measured on two occasions due to access issues.

As for the Mill Rd/Blacks Rd well transect, the south side showed a relatively flat gradient adjacent to the river with a stronger positive gradient moving from the inland wells towards the river, while the northern side of the transect generally showed water levels lower than the river. Water levels in the most inland wells on the transect (K37/3091 and the Mill Rd Pipe) were about 2 m below the river and Mill Rd piezometers. There was an upwards gradient from well K37/3091 to the Mill Rd Pipe of about 10^{-3}-10^{-4}, with a slightly stronger positive gradient from the Mill Rd Pipe to the far Mill Rd piezometer (10^{-3}). There were small fluctuating positive and negative gradients between the close and far Mill Rd piezometers and the river. It is worth noting that there is an irrigation well located in between the far and close Mill Rd piezometers. The depth of this well is unknown, but it is believed to be relatively shallow (<10m). This well was pumped throughout the study period at a rate of 40

L/s. It is possible that this pumping may have affected water levels in the nearby piezometers, however, based on the results there was no obvious effect. From the far Blacks piezometer, there was a negative gradient to the close Blacks piezometer, which then had a positive gradient to the river. As a result, the close Blacks piezometer appeared to be in a depression. This lower water level may be a result of the vegetation surrounding the piezometer taking up groundwater, as the well was installed very close to large trees and shrubs (Rosenberry & LaBaugh, 2008). However, it is also worth noting that several of the other piezometers were installed in vegetated locations, though arguably the close Blacks piezometer site was the most heavily vegetated. The height of this piezometer was 7 mm higher than the river piezometer, so a lower topographic height of the ground would not explain the lower water level on the river bank, however it is possible that this lower water level is a reflection of the highly heterogeneous substrate.

In terms of characterising the study locations as gaining or losing reaches of the river in respect to groundwater, the upstream Sheates Rd/Ollivers Rd transect shows a neutral relationship between groundwater and surface water on the south side of the transect and a gaining relationship on the north side (i.e. groundwater flowing to the river). On the downstream Mill Rd/Blacks Rd transect, the river appears to be losing flow to groundwater on the south side of the transect, whereas on the north side there is a neutral relationship between surface water and groundwater. To some degree this result aligns with findings from previous studies that theorise that some of the North Branch flow is being lost to the southeast into the South Branch of the river then the South Branch is losing some flow to groundwater to the south (Dommisse, 2007; P. Durney, personal communication, 24 Jan 2017; G. Horrell, personal communication, Apr 2017).

As shown in Appendix B, the piezometric survey results have been plotted against river flow and rainfall in the upper South Branch catchment. While these simple graphs do not show evidence of a statistical correlation between well levels, flow and rainfall, they do give a broad picture of how water level increases and decreases on the well transects aligned with fluctuations in upstream river flow and rainfall events during the survey period. Generally, when river flows were higher and rain had fallen in the catchment within the preceding two days, higher water levels were recorded in the piezometers relative to surveys when river flow and rainfall were lower. When comparing trends between the two well transects, the highest water levels recorded on the Mill Rd/Blacks Rd transect were on the 11 October survey, whereas the peak water levels recorded in the Sheates Rd/Ollivers Rd transect were on the 19 September survey when there was the most significant rainfall and river flow levels of the entire study period. In other words, when compared to the Sheates Rd/Ollivers Rd transect, the Mill Rd/Blacks Rd wells had a greater response to a smaller rain event (on 11 October).

While there appears to be a correlation between river flow and piezometric levels, this may simply be a reflection of flow being higher after rainfall events. Given the piezometer levels also had an apparent correlation with rainfall, it is suspected that the increase in the levels in these shallow wells was in response to rainfall given the highly permeable substrate (refer to section 5.2.2 for horizontal *K* values and 5.3 for vertical flux values). It is also important to note that the results of the piezometric surveys only provide spot measurements. A continuous record of water levels in the wells would provide a better basis for comparison with river flow and rainfall.

While it would be possible to carry out an in-depth statistical analysis of potential correlations between piezometric levels and river flow or rainfall, this would be complex due the multitude of factors potentially affecting water levels in wells (D. Gerhard, personal communication, 18 Jan 2018). Several aspects would need to be included in a statistical model, such as the individual well locations, which transect they lie on, and antecedent rainfall and flow for multiple days preceding water level readings. As recommended by University of Canterbury's Statistical Consulting Unit, this analysis may require a hierarchical linear model (if the relationship is linear) or another type of model which would likely be complex and beyond the time available for this thesis' data analysis.

5.2.2 Slug testing

Results from the slug tests performed on mini-piezometers in this study were presented in section 4.3. Average horizontal conductivity (*K*) values ranged from 5 to 148 m/day across all the mini-piezometers tested. These *K* values are in line with reference values for sandy gravel aquifers from several sources including Heath (1983), which shows *K* values between $10\text{-}10^3$ m/day for materials ranging from fine sand to gravel. Domenico and Schwartz (1998) provide *K* values for fine sand to gravel of $10^{-2}\text{-}10^3$ m/day (Table 5.1), which are also in line with the results from the slug testing.

Table 5.1. Representative values of hydraulic conductivity for various sediment types. Adapted from Domenico and Schwartz (1998)

Material	**Hydraulic Conductivity (m/day)**
Gravel	$10\text{-}10^3$
Coarse sand	$10^{-2}\text{-}10^2$
Medium sand	$10^{-2}\text{-}10$
Fine sand	$10^{-2}\text{-}10$

The *K* values derived from the slug tests also align well with previous Canterbury studies, however there have been limited published *K* value estimates specific to the Ashburton area. Dann et al. (2008) estimated average *K* values across the highly heterogeneous alluvial Canterbury Plains aquifer using pumping and tracer tests. Their results provided an average *K* value of ~100 m/day across the aquifer, however they estimated *K* values two orders of magnitude higher (~8,400 m/day) in the permeable channels that are typical in the alluvial Canterbury Plains aquifer. In a report on a groundwater model for the Hinds Plains, which refers to the plains between the Hakatere/Ashburton River and the Hinds River to the south (and continues south to the Rangitata River south of the Hinds), Durney et al. (2014) estimated *K* values across the Hind Plains to be on average 26.9 m/day with an upper limit of 194 m/day. However, Durney et al. (2014) noted that there is a degree of uncertainty associated with estimating the hydraulic conductivity for several reasons including the complex subsurface geology, very high transmissivity, uncertainty around aquifer thickness and wells often being screened in multiple aquifers. Also, this average may be somewhat lower than typical values near the Hakatere/Ashburton River as the lower Hinds Plains are characterised by fine sediments, and thus lower *K* values.

It is important to note that slug tests only measure the horizontal conductivity of an aquifer, and because aquifers are generally anisotropic (i.e. they are not equally conductive in all directions), vertical hydraulic conductivity is often much smaller (Rosenberry & LaBaugh, 2008). This is particularly the case in the alluvial aquifer of the Canterbury Plains where there are estimates of a minimum 1:3 ratio of vertical to horizontal conductivity (Durney et al., 2014). As mentioned in section 4.3, a ratio of 1:100 was used in the calculation of *K* values, as this is believed to be a conservative value given the ratio in the open framework gravels might be 1:1000 (P. Durney, personal communication, 21 Nov 2017).

There are several limiting factors that affect the confidence around the *K* values based on the slug testing results. Slug tests are only point-scale applications, so it can be difficult to extrapolate results on a broader scale (Rosenberry & LaBaugh, 2008). This may particularly be the case for highly heterogeneous aquifers, such as those typical in braided river environments. Also, after discussions with several Canterbury-based hydrogeologists, some felt the *K* values obtained from the slug testing were too low, while some thought they were within a typical range. One concern with the *K* values being too low was that possibly the screen on the mini-piezometers was too small and restricted the flow of water during the slug test. While this is possible, it seems unlikely given the quick recovery of the water levels. This could be tested by filling the piezometers with water and recording how long they take to drain.

5.2.3 Physicochemical sampling

Results from the physicochemical sampling campaign were presented in section 4.5. In general, the analysis showed similar chemistry in the river and nearest mini-piezometers, while the groundwater wells further inland were less chemically similar to the river. This may indicate a high degree of connectivity between the river and the adjacent shallow groundwater, particular during this sampling period in September and October 2017, which was a period of high rainfall and snowmelt.

The following paragraph discusses the findings on the Sheates Rd/Ollivers Rd transect. Temperature on this transect was only measured in the river and mini-piezometers, as there was no direct access to well K37/2382 or K37/0133 to take probe measurements. On average, the river had the highest mean temperature at 11.3^{o}C, while the close piezometers had the lowest mean temperatures on the transect at 9.7^{o}C (Sheates) and 9.8^{o}C (Ollivers). The mean temperatures in the far piezometers fell in the middle at 10.4^{o}C (Sheates) and 10.5^{o}C (Ollivers). Mean pH readings were highest in the river (6.92) and the Ollivers close piezometer (6.91). There was a drop in mean pH in the Sheates close piezometer (6.33) and the Ollivers far piezometer (6.48). The mean pH was similar to the river in well K37/0133 (6.89), while values on the southern end of the transect were lower: 6.44 in the Sheates far piezometer and 6.25 in well K37/2382. Mean conductivity readings were lowest in the river (71.6 µS/cm) and generally increased with distance from the river. The Ollivers close piezometer was only slightly higher than the river at 77.3 µS/cm, while the Sheates close piezometer was significantly higher at 114.6 µS/cm, which may reflect the influence of the groundwater spring near this well. The Sheates far piezometer had a similar reading at 115.8 µS/cm, and there was an increase in well K37/2382 to 185.7 µS/cm. On the north side, the most inland wells had values of 132.5 µS/cm (Ollivers far piezometer) and 126.2 µS/cm (K37/0133). Mean nitrate-nitrogen readings were similar in the river (0.7 mg/L) and two adjacent piezometers (0.4 mg/L in the Sheates close piezometer and 0.8 mg/L in the Ollivers close piezometer). Mean nitrate-nitrogen readings increased with distance from the river. Readings on the north end of the transect were 1.9 and 1.8 mg/L for the Ollivers far piezometer and well K37/0133, respectively. The highest nitrate-nitrogen readings on the transect were in well K37/2382 with an average of 3.6 mg/L.

On the Sheates Rd/Ollivers Rd transect, conductivity and nitrate-nitrogen appear to show the clearest trends that may be useful for identifying groundwater and surface water sources. Both of these parameters show lower concentrations in the river that increase with distance from the river. Temperature and pH do not appear to have been as useful in this case.

The following paragraph discusses results on the Mill Rd/Blacks Rd transect. There was not an obvious trend in temperature on this transect with mean temperatures at the river, both

Mill Rd piezometers and the Blacks far piezometer ranging from 10.9-11.4°C. Temperatures were on average 10.2°C in both well K37/3091 and the Blacks close piezometer. Mean pH values were highest in the river (7.27) and generally decreased with distance from the river, with the exception of well K37/3091, which had a slightly higher mean pH (6.76) than the Mill far piezometer (6.53). As would be expected for surface water, particularly during this period of high rainfall and snowmelt, the river had low conductivity values (85.4 µS/cm), with similarly low readings in the Mill close piezometer (83.6 µS/cm) and Blacks close piezometer (105.0 µS/cm). There was a moderate increase in conductivity in the far piezometers with values of 220.7 µS/cm (Mill Rd) and 167.0 µS/cm (Blacks Rd). There was a considerably higher mean value in well K37/3091 of 426.2 µS/cm, which is not surprising given the high nitrate readings as discussed below. Mean nitrate-nitrogen readings were lowest in the river (1.1 mg/L) and two adjacent piezometers (1.0 mg/L in the Blacks close piezometer; 1.1 mg/L in the Mill close piezometer). There was an increase in nitrate-nitrogen with distance from the river. The far piezometers had similar mean values of 3.9 mg/L (Mill far piezometer) and 3.7 mg/L (Blacks far piezometer). Well K37/3091 consistently had the highest nitrate-nitrogen readings of all sites sampled in both transects with an average of 14.8 mg/L.

As with the Sheates Rd/Ollivers Rd transect, conductivity and nitrate-nitrogen appear to show the clearest trends in concentrations across the Mill Rd/Blacks Rd transect. Thus, these parameters may prove the most useful in characterising groundwater-surface water exchange at these sites in comparison to all parameters measured.

It is important to note that while there was an attempt to collect data at the same time of day during each sampling run, there may be variations in the measured river temperatures and pH levels because of daily variability in these parameters due to weather and the time the samples were collected.

Groundwater in Canterbury can also display seasonal variations in concentrations of some chemicals. Concentrations of dissolved ions are often highest in the spring months when there is higher rainfall and irrigation resulting in land surface runoff leaching salts from the soil and percolating to groundwater (Hanson & Abraham, 2013). Thus, given this sampling occurred during irrigation season and in a period of high spring rainfall, the higher concentrations of some parameters may reflect this seasonal trend.

The results of this sampling are largely within the range of values in Environment Canterbury's annual regional groundwater quality survey results for 2016 (Hanson, 2017). The results from groundwater samples taken in the current survey have been compared with the 2016 Environment Canterbury results in Table 5.2. Temperature and conductivity in the groundwater wells measured in the current survey were slightly below median values in the 2016 Environment Canterbury survey, which may be a reflection of surface water mixing in the shallow groundwater. The median nitrate-nitrogen value of 1.6 mg/L measured in this study was lower than the median of 2.9 mg/L in the Environment Canterbury study, but the highest value measured in the current study of 21.5 mg/L (from well K37/3091) exceeded the maximum value in the Environment Canterbury survey.

Table 5.2. Comparison of groundwater quality parameters in the current study and the 2016 Environment Canterbury (ECan) regional survey

		Current Sampling		**ECan 2016 Survey***	
Parameter	**Units**	**Median**	**Range**	**Median**	**Range**
Temperature	°C	10.4	8.9-12.0	12.5	7.4-17.8
pH		6.57	6.07-7.5	6.7	5.2-8.7
Conductivity	µS/cm	123.5	73.04-430.0	192	22-1094
Nitrate-Nitrogen	mg/L	1.6	0.2-21.5	2.9	<0.05-19.2

*Data from M. Hanson (2017).

One of the objectives set out in this study was to establish whether shallow groundwater or the river at the study sites served as a source of water quality contamination to the river or shallow groundwater, respectively. Based on the results discussion presented above, it does not appear that shallow groundwater is adversely impacting surface water quality at the study sites. Nor does it seem that the river is serving as a source of contamination to the groundwater. Rather, it appears that the river at these sites may be having a dilution effect on shallow groundwater close to the river, serving as a contamination buffer from poorer water quality further inland.

In terms of comparison of results to water quality standards, drinking water regulations, recreational water quality, and suitability for aquatic life may all be relevant. In regards to the parameters measured here that are included in the New Zealand Drinking Water Standards (Ministry of Health, 2008), the median pH of groundwater and surface water sampled—6.57 and 6.88, respectively—was below the desired range of 7.0-8.5 for drinking water. Median nitrate-nitrogen concentrations in both groundwater and surface water—1.6 and 0.9 mg/L, respectively—were both below the Maximum Acceptable Value (MAV) of 11.3 mg/L, however one well (K37/3091) exceeded the MAV in seven out of nine samples taken. In regards to suitability for recreation in the river at the study sites, temperature and pH are included in the Australian and New Zealand Environment and Conservation Council (ANZECC) (2000) guidelines, and the median values obtained in this study were within the guidelines ranges of 15-35°C and pH of 5.0-9.0. In regards to the quality of the water for aquatic life, the New Zealand National Policy Statement for Freshwater Management 2014 (Ministry for the Environment, 2017) has a maximum acceptable level of nitrate-nitrogen in rivers of 6.9 mg/L; however, there may be toxic effects on the most sensitive species at levels above 1.0 mg/L. Median values of nitrate-nitrogen in this study were 1.6 and 0.9 mg/L for groundwater and surface water, respectively. While these concentrations are below the national guideline levels, they may pose a risk to highly sensitive aquatic species. Lastly, the ANZECC (2000) guidelines recommend a pH range in surface water of 7.3-8.0 in upland rivers, whereas the median pH measure in the river at the study sites was below this at 6.88.

5.3 Temperature probes

Results from the vertical temperature probe sampling were presented in section 4.4. To the author's knowledge, there have been no known uses of diurnal temperature signal analysis previously in braided rivers, so this has served as a test case to assess the effectiveness of this method for investigations of groundwater-surface water exchange in this type of environment. Overall, the diurnal signal analysis produced variable results. As discussed in section 4.4, "reliability" was assessed based on the size of the amplitude ratios (A_r) of the sensor pairs in a given probe. As the calculation of flux is based on A_r, when A_r approaches 1, the flux cannot be calculated. Several of the datasets (e.g. Ollivers Rd 29 Aug-15 Sept; Blacks

Rd 29 Aug-15 Sept & 4-26 Oct) showed unreliable flux estimates in the beginning of the data collection period and more reliable estimates later in the time series. In these cases, the flux estimates oscillated widely in the beginning and then became more constant, which corresponded with a decrease in A_r. Some datasets did not produce any reliable flux estimates.

On the Sheates Rd/Ollivers Rd transect, the first sampling run on 4-11 July did not produce reliable results, whereas the subsequent two sampling runs, on 29 August to 15 September and 4-26 October produced more reliable flux calculations. The probe at Ollivers Rd on the left side of the river showed vertical flux in a downwards direction at rates ranging from 0.086-0.604 m/day. The probe on the opposite side of the river at Sheates Rd showed vertical flux in the upwards direction at a rate of 0.432-1.555 m/day. In other words, this may indicate that river water is flowing to groundwater on the north side of the river, while on the south side of the river, groundwater is seeping into the river.

On the Mill Rd/Blacks Rd transect, the probe at Blacks Rd produced reliable flux results in all three sampling runs, while the probe at Mill Rd only produced reliable results in the 5-15 September sampling run. The Blacks Rd probe showed downwelling flux in the second two sampling runs, while it showed upwelling on the first sampling round in July. Arguably, the downwards flux direction may be more reliable given this was the result in two of three rounds. Downwelling rates were 0.259-2.592 m/day while upwelling rates were 0.864-1.037 m/day. The Mill Rd probe showed downwards flux at a rate of 0.864 m/day. In summary, the sampling on this transect may indicate river water flowing to groundwater on the north side of the river in two of three sampling rounds, while the results on the south side were less reliable but also showed that river water may be flowing to groundwater.

A limitation of diurnal temperature signal analysis is that it is difficult to conclude with certainty that the calculated flux rate represents net surface water-groundwater exchange rather than hyporheic zone flow (i.e. water that leaves the river and returns through adjacent or sub-surface sediments through relatively short flow paths) (Irvine et al., 2017).

Scouring or deposition of sediment around the temperature probes during data collection is also relevant to consider. Ultimately it is the sensor spacing that is crucial for this analysis, rather than actual depth (Hatch et al., 2006); however, it is an issue if any sensors are exposed due to scour (i.e. they are no longer in the streambed). Before the temperature probes were removed at the end of each round of data collection, the depth to the streambed from the top of the probe was measured to assess if there had been scour or deposition during sampling. In several cases there had been deposition of <5 cm, with one exception of 37.5 cm of deposition around the Mill Rd probe during the 4-26 October sampling run. As noted above, the results from this probe were unreliable, which may be related to this large amount of deposition. Regarding streambed scour, three probes were affected. The probe at Ollivers Rd during 4-11 July had 1.7 cm of scour, however the flux rates for this probe were not reliable due to issues with the A_r. During 29 August to 15 September, the Ollivers Rd probe had 6 cm of scour, and the Blacks Rd probe had 1.5 cm of scour. As a result, the top sensors were not used for flux analysis. It is also important to note that the probe at Sheates Rd during 4-26 October was found to be at a 45° angle in the streambed at the end of the sampling run as the probe was pulled by plant debris flowing down the river in a storm.

Errors in the flux calculation can also be introduced by sudden changes in river stage (Irvine et al., 2017), such as after rainfall events. This can result in non-steady flux rates being calculated or changes in estimated flux direction, which may be real as a natural consequence of stream flooding (Rau et al., 2015). Thus, it is very useful to record stream stage or flow data concurrently with temperature time series. Hydrographs for the three flow recorders upstream of the study sites are presented in Appendix C. The 4-11 July temperature round had slowly decreasing river flow levels through the period, so changes in river flow were unlikely to affect flux calculations. The period between 29 August and 15 September experienced two moderate increases in flow four and nine days into the data collection, which did appear to affect flux calculations in the first week of the time series, particularly for the Blacks Rd probe. However, these affected values were not reported as the final flux rates. Finally, there was a large storm and a smaller one on the fourth to eighth days of data collection during 4-26 October. This resulted in a sudden increase in flux rates for all probes, as well as a change in direction for the Sheates Rd probe. Flow levels in the

South Branch gradually decreased after this storm, and the flux estimates in the Ollivers Rd probe reflect this downwards trend.

Another potential source of error with the flux rates provided here is incorrect thermal properties of the streambed sediment used as inputs in the VFLUX analysis (Rau et al., 2010) such as the porosity, thermal conductivity or specific heat capacity. It is also important to highlight again that the Hatch (2006) method assumes that flow is one dimensional.

5.4 Results comparison

An objective of this study was to compare the results obtained from each of the methods to help assess their effectiveness for characterising groundwater-surface water exchange at the study sites. In general, the results provide a complex picture of the physical processes occurring in this area (refer to Table 5.3 and Figures 5.1-5.2).

Table 5.3. General comparison of results across methods

Location	Piezometric Surveys	Diurnal Temperature Signal Analysis	Chemical Analysis
Sheates Rd/Ollivers Rd - North Side	River gaining flow from groundwater	River losing flow to groundwater	River losing flow to groundwater
Sheates Rd/Ollivers Rd - South Side	No apparent gradient	River gaining flow from groundwater	River losing flow to groundwater
Mill Rd/Blacks Rd - North Side	No apparent gradient	River losing flow to groundwater	River losing flow to groundwater
Mill Rd/Blacks Rd - South Side	River losing flow to groundwater	River losing flow to groundwater/unclear results	River losing flow to groundwater

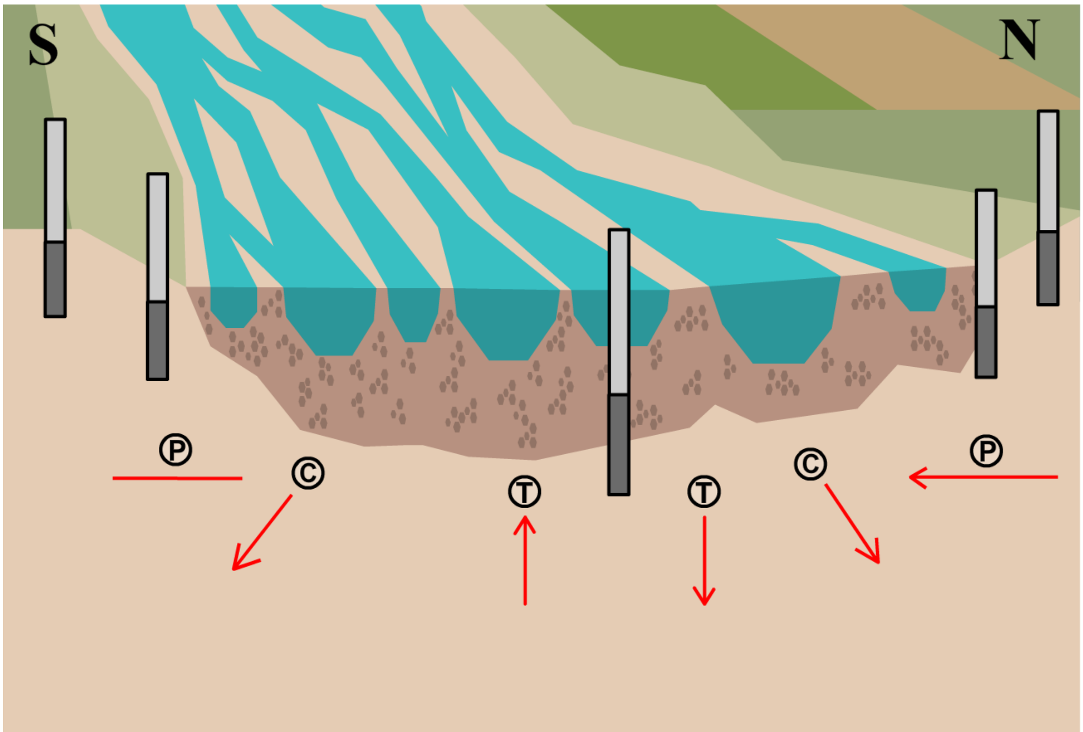


Figure 5.1. A simplified conceptual diagram of results on the Sheates Rd/Ollivers Rd transect. The arrows indicate the direction of water flow based on results from the various methods. P = piezometer results; C = chemistry results; T = temperature probe results. Image source: Steve Coluccio

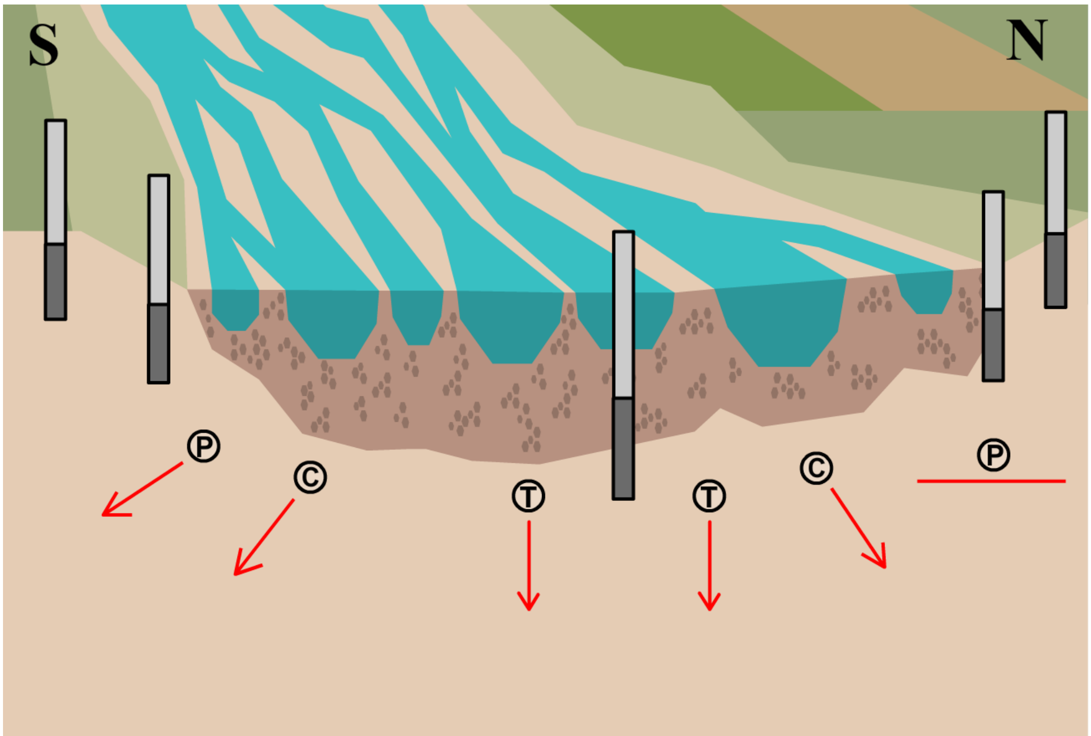


Figure 5.2. A simplified conceptual diagram of results on the Mill Rd/Blacks Rd transect. The arrows indicate the direction of water flow based on results from the various methods. P = piezometer results; C = chemistry results; T = temperature probe results. Image source: Steve Coluccio

The results did not always agree across methods, which at least in part is likely to be a reflection of this heterogeneous system and that fact that it is difficult to use point-scale methods only to describe this level of complexity.

As shown in Figure 2.7, the South Branch immediately above, below and between the two sampling transects is considered to be gaining based on past concurrent flow gauging. The current understanding is that some of these gains are coming from upstream losses on the South Branch. That is, the South Branch loses some flow to groundwater, and this reappears as springs on the south side of the South Branch. Some portion of these gains are also believed to be coming from the North Branch of the river. However, it is also thought that some South Branch flow is lost to the south across the Ashburton-Hinds plains.

Interestingly, results support all of the theories outlined in the paragraph above. Rather than this being strictly a gaining reach of the river, for instance, it may gain in parts and lose in others. There may be multi-scale processes operating simultaneously. The piezometric surveys on the north end of the Sheates Rd/Ollivers Rd transect support the theory that groundwater is flowing from the North Branch to the South Branch, however it should be highlighted that there were only two measurements on the northernmost well (K37/0133) of this transect that most strongly showed this trend. In contrast, the water levels in the far piezometer on Blacks Rd were very similar to the river. However, this piezometer was only 0.2 m higher than the piezometer in the river, whereas well K37/0133 was 9.1 m higher than the river piezometer. Thus, it is logical that this well shows a steeper hydraulic gradient with the river. Regarding the possible gains on the south side of the river, groundwater may be upwelling at the southern end of the Sheates Rd/Ollivers Rd transect. The diurnal temperature signal analysis produced upwelling flux rates, which is plausible given the spring very near to the Sheates Rd close piezometer.

In regard to losses from this reach of the river, the south side of the Mill Rd/Blacks Rd transect showed a clear losing trend across all methods. The diurnal signal analysis characterised three of the sampling locations as downwelling: Ollivers Rd, Mill Rd and Blacks Rd. As mentioned earlier, it is difficult to assess whether this flux is net surface water-groundwater flow or hyporheic exchange. It is possible that in these locations, surface water is flowing to groundwater through the base of the streambed. Alternatively, river water may for some period of time flow within the riverbed (i.e. the hyporheic zone) and later re-emerge into the river. It is also plausible that both processes could be happening: some portion of flow is lost to groundwater while some is throughflow in the streambed.

5.5 Effectiveness and limitations of study design and methods

Overall, the study design has been considered successful in improving the understanding of groundwater-surface water interactions in the South Branch of the Hakatere/Ashburton River. From a practical perspective, the equipment worked well. The mini-piezometers and vertical temperature probes were easy to build. It was possible to install them with relative ease into the coarse gravel streambed and margins, and similarly, it was not difficult to remove them with the appropriate equipment. The vertical temperature probes and some of the mini-piezometers were thoroughly tested for their ability to withstand flooding. On several occasions, equipment was found with gravel piled at the bottom of pipes or scoured out, and often the pipes were covered with bushes and plant debris. Despite this, no equipment was washed down the river, which is considered a great success of this project. The materials used to build the mini-piezometers and temperature probes were relatively cheap, particularly when compared to similar tools available commercially.

Site selection was an important component of the study design and several factors were considered, such as gravel size; estimated magnitude of gains and losses in river reaches; and suitability of channels for sampling. However, likely the most weighted factor was access. For much of the sampling, vehicle access to at least the edge of the river greatly improved the ease and efficiency of the work, so sites with public or private road access were preferred. Some of the sampling locations required access on private land, and landowners were very helpful and cooperative with allowing the research to happen on their properties.

The braided river showed its dynamic nature during this project in terms of high flows, shifting channels and sediment movement. The temperature probes needed to be installed in channels that would not become dry for the duration of data collection, and it was difficult to predict where these locations were. Also, the mini-piezometers installed closest to the river were at times inundated with river flow (Figure 5.3). This was despite best efforts to choose sites a sufficient distance from the river's edge. Access into the river was key, particularly to install and remove the temperature probes as well as sample the river piezometers. Despite the attempt to install this equipment in accessible locations, there were times when river flows were too high to reach equipment, and channel shifting exacerbated this issue.

Figure 5.3. High river flows inundating the Mill Rd close piezometer (in pink) on 19 Sept 2017. Photo: Graeme Horrell

It was difficult to identify suitable shallow wells for sampling for several reasons. Many shallow wells (<10 m) on the Canterbury Plains are no longer in use, so either they have been covered, capped off or are no longer suitable for sampling. Many active wells were also not suitable for sampling for a variety of reasons such as poor access or large casing diameters (which would have made well purging impractical). Many wells were too far from the mini-piezometer transects and thus would not have provided useful information. Of the four wells used in the sampling program, two had down-well pumps and narrow well casings. As a result, they could not be sampled directly with probes, so temperature measurements could not be taken, which was a considerable drawback. Also, there was very little room between the down-well pumps and the well casings to fit the water level meter. This became so difficult that water level measurements in these two wells were no longer taken part way into the program. Given this difficulty in finding suitable existing wells, mini-piezometers with a similar design to those used here may be preferable when sampling shallow groundwater in future studies.

Regarding the results from the diurnal temperature signal analysis, arguably it would be very useful from a water management perspective to extrapolate the flux estimates to a reach scale. The current study was not designed so that this would be possible, however previous work by Lautz and Ribaudo (2012) examined scaling up of point-in-space temperature profiling data.

To account for the limitations described in the paragraph that follows, the study was designed to produce robust results. Sampling was conducted on multiple occasions to allow for flexibility if there were failures in equipment or to discard anomalous readings. In general data points were averaged to better represent overall results. Standard sampling protocols were followed where applicable, such as New Zealand's national standards for groundwater sampling (Daughney et al., 2006). Sampling was also conducted at multiple locations to provide a richer picture of physical processes at the study sites.

As expected, there were a lot of factors at the study sites that may have affected results. There was a high amount of rainfall and snowfall in the catchment, which resulted in high river and groundwater levels. In most cases, investigations of groundwater-surface water exchange are most effective during periods of baseflow where there is no influence of precipitation. Arguably, it may also be useful to observe how surface water and groundwater appear to interact during high-precipitation periods, but this is likely to have influenced the results to a significant degree and complicated the determination of seepage directions. At least one of the study sites (Mill Rd) had a nearby shallow well that was actively used during the sampling program, which may have affected static water levels or groundwater-surface water flow near this site. Also, there are numerous small surface water bodies near the study sites: stock water and irrigation races; spring-fed streams; and natural and manmade drains. These mostly flow into the river as opposed to out, and they make it more difficult to interpret the results. The thick vegetation on the river margins may have taken up shallow groundwater during the study, interfering with the natural flow between the river and groundwater. In addition, the heterogeneous nature of the riverbed and shallow aquifer complicates the interpretation of the mostly point-scale data as it is difficult to extrapolate conclusions on a broad scale. Also, it is often difficult to assess whether net surface water-groundwater exchange or hyporheic flow is being measured. The complexity of this environment also makes it difficult to draw conclusions based on the two sampling transects.

5.6 Review of study objectives

This section looks back to the study objectives initially laid out in section 1.1 and reviews whether they were achieved.

1) Install mini-piezometers and vertical temperature probes in the river and its margins.

Mini-piezometers and vertical temperature probes were purpose built to be effective in a braided river setting and carry out the sampling program. They were successfully installed into the river and the margins at the study sites, and they were a useful source of data for the study.

2) Carry out flow gauging in the South Branch of the Hakatere/Ashburton River to determine reaches that are gaining groundwater and those that are losing river flow to groundwater.

As previously discussed, this research program was carried out during a period of high rainfall and snowfall. This resulted in river levels being too high to carry out flow gauging. In order for the gauging to effectively measure streambed seepage, the river needs to be at minimum flow levels so there is no influence of rainfall. Also, as discussed in section 4.6, based on results from this thesis and previous work, there is reason to believe that net seepage along the seepage runs would be much less than the margin of error associated with the flow gauging. However, flow recorder data from the Hakatere/Ashburton River and tributaries was used to compare to results from the piezometric surveys and diurnal temperature signal analysis.

3) Use these methods to identify areas of groundwater-surface water connectivity and calculate rates of seepage through the streambed.

Data gathered from the piezometric surveys, diurnal temperature signal analysis and physicochemical sampling have been analysed to qualitatively describe groundwater-surface water exchange at the study sites. From slug tests carried out on the mini-piezometers, hydraulic conductivity values were calculated, which provide an estimation of the rate of horizontal groundwater flow. The diurnal signal analysis produced flux rates at the study sites that estimate the direction and rate of vertical flow through the streambed.

4) Carry out physical and chemical analysis of the water to enhance the understanding of water and nutrient sources at the study sites.

Temperature, pH, conductivity, nitrate-nitrogen and dissolved reactive phosphorus were sampled on three occasions on the two transects. Values were compared between the river and groundwater wells to shed light on surface water and groundwater mixing.

5) If necessary, refine the design of the techniques to make them more suitable for use in braided rivers.

There was considerable time spent on the design of the equipment—particularly the mini-piezometers and vertical temperature probes—to enhance their suitability for use in braided rivers. Equipment was tested before being deployed and designs were refined as needed. Repeated sampling allowed for the improvement of equipment and techniques as the study progressed.

6) Critically assess the usefulness of these tools for groundwater-surface water investigations in braided rivers.

Section 5.5 of this thesis was dedicated to discussing the effectiveness and limitations of these techniques and the study design.

5.7 Future research

There are many possibilities for further research to expand the knowledge gained through this thesis both in terms of the Hakatere/Ashburton River specifically and groundwater-surface water interactions in braided rivers more broadly. It would be interesting to test different arrangements of the mini-piezometers, such as nesting them at different screen depths to determine the direction of vertical hydraulic gradient. Extending the well transects further inland might reveal more information about the horizontal gradient of water flow between the river and groundwater. Installing the temperature probes lengthwise down the river channel could provide useful insight into flux rate variation. Also, using a larger number of temperature probes would help overcome the limitations of this point-scale method. Further, it would be very interesting to apply a method such as that of Lautz and Ribaudo (2012), in which temperature probes were installed in a grid pattern to estimate seepage on a reach scale.

There are various methods that could be used in future studies in conjunction with some or all of the methods used in this thesis that have been used successfully in braided rivers before or appear promising. Airborne thermal imaging would be useful to gain a broad-scale view of areas of groundwater seepage to the river that could then be used to apply finer scale methods. Fibre optic distributed temperature sensing could be another useful method for braided river applications at various scales. The fibre optic cables can be placed down long stretches of the river to measure horizontal temperature variability, or they can be wrapped in coils and used as point measurements. There are several naturally occurring chemical tracers that would be useful to measure. Stable isotopes such as oxygen-18 have successfully been used to identify water sources, while radon analysis is a promising newer method for identifying areas of exchange in braided rivers. Measurement of radon in known areas of upwelling in the streambed may shed light on whether seepage is true groundwater or hyporheic flow, such as demonstrated in Acuña and Tockner (2009). Finally, using data gathered from these various methods as inputs to more sophisticated models of braided rivers and surrounding groundwater systems would be very useful.

Chapter 6. Conclusion

This research used a multi-method approach to examine groundwater-surface water interactions in the Hakatere/Ashburton River on the South Island of New Zealand. Inexpensive and easy-to-deploy techniques were tested for their effectiveness in braided rivers, and their design was refined to better suit this dynamic environment characterised by coarse-gravel streambeds, heterogeneous substrate, shifting channels and fluctuating flow levels.

Mini-piezometers were installed in the riverbed and margins in horizontal transects at two sites on the South Branch of the river. The piezometers were used to carry out piezometric surveys, water sampling and slug testing, and this data was complemented with sampling of nearby shallow groundwater wells. The data was used to establish the direction and magnitude of the hydraulic gradient between the shallow groundwater levels and the river. Pneumatic slug tests were conducted on the mini-piezometers on the river margins, and from this, hydraulic conductivity values were estimated.

Vertical temperature probes were installed in the riverbed at the two study sites. iButton temperature sensors were deployed from 1-16 cm deep in the streambed and took temperature readings at 10-minute intervals for periods of one to three weeks. The temperature time series data was analysed using the diurnal signal processing software VFLUX. For each temperature probe location, the vertical direction of flux was determined and the flux rate was calculated.

Physicochemical sampling was carried out in the river at the two sites, and in the mini-piezometers and groundwater wells. Temperature, pH, conductivity, nitrate-nitrogen and dissolved reactive phosphorus were analysed in the field using Orion and Hach probes, and a Hach portable colorimeter.

As an initial objective of this study, flow gauging was intended to be carried out upstream and downstream of both study sites to calculate the streambed conductance along these two river reaches. However, due to a season of high rainfall and snowfall in the catchment, at the time of writing, the river flow level had not yet fallen sufficiently to accurately measure seepage through the streambed.

Results from the various methods painted a complex picture of groundwater-surface water processes at the study sites. At the upstream Sheates Rd/Ollivers Rd site, results estimated both gains and losses in the river, while the site at Mill Rd/Blacks Rd showed a more consistent losing trend. These results are mostly based on data collected on a point scale, so to draw conclusions about processes occurring at a larger scale, it would be necessary to carry out broader scale methods such as flow gauging, chemical tracer analysis or airborne thermal imaging. Additionally, it would be very useful to deploy the methods applied in this study on a larger scale, such as lengthwise along the river, which would enhance the ability to draw wider conclusions about groundwater-surface flow paths and seepage rates.

The equipment used in this study proved sufficiently robust and effective to be used in the dynamic, coarse-gravel environments of braided rivers. The designs developed here may prove useful in future studies, particularly where there is a need for inexpensive and easy-to-install and operate techniques.

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Appendix A. Sampling location information

Table A.1. Location of mini-piezometers

Well ID	NZTM Northing	NZTM Easting	Elevation (m.a.s.l.)
Blacks Close Piezo	5144357.217	1493608.977	138.868
Blacks Far Piezo	5144645.336	1493967.611	139.125
Mill Rd Close Piezo	5144256.605	1493383.853	138.430
Mill Rd Far Piezo	5144153.181	1493196.663	138.937
Mill Rd River Piezo	5144282.291	1493444.349	138.861
Ollivers Close Piezo	5147287.241	1491949.654	157.691
Ollivers Far Piezo	5147319.596	1492090.139	157.038
Sheates Close Piezo	5147227.395	1491701.280	157.052
Sheates Far Piezo	5147145.224	1491572.591	157.579
Sheates River Piezo	5147228.190	1491777.360	156.394

Table A.2. Location and well details for groundwater wells

Well ID	Location	Depth	Diameter	Approx. distance to river	NZTM Northing	NZTM Easting	Elevation (m.a.s.l.)
K37/0133	Ollivers Rd	6.09 m	7.5 cm	0.4 km	5147452.290	1492248.598	165.502
K37/2382	Sheates Rd	5.00 m	3.5 cm	0.6 km	5146863.542	1491198.817	157.158
Mill Rd Pipe	Mill Rd	~ 2.00 m	~15 cm	1.2 km	5143189.145	1492487.524	137.370
K37/3091	Mill Rd	15.9 m	7 cm	1.8 km	5142849.038	1492044.086	136.686

Table A.3. Location of temperature probes

Temperature Probe	Sampling Dates	NZTM Northing	NZTM Easting
Probe 1 - Ollivers Rd	4-11 July 2017	5147332.416	1491888.881
Probe 1 - Ollivers Rd	29 Aug-15 Sept 2017	5147270.859	1491929.297
Probe 1 - Ollivers Rd	4-26 Oct 2017	5147270.833	1491927.688
Probe 2 - Sheates Rd	4-11 July 2017	5147135.018	1491773.846
Probe 2 - Sheates Rd	29 Aug-15 Sept 2017	5147158.094	1491758.188
Probe 2 - Sheates Rd	4-26 Oct 2017	5147163.647	1491758.098
Probe 3 - Blacks Rd	4-11 July 2017	5144515.451	1493427.786
Probe 3 - Blacks Rd	29 Aug-15 Sept 2017	5144513.178	1493424.606
Probe 3 - Blacks Rd	4-26 Oct 2017	5144510.983	1493426.25
Probe 4 - Mill Rd	4-11 July 2017	5144393.424	1493300.294
Probe 4 - Mill Rd	5-15 Sept 2017	5144453.09	1493280.039
Probe 4 - Mill Rd	4-26 Oct 2017	5144448.673	1493281.718

Appendix B. Comparison of piezometric surveys with river flow and rainfall

Sheates Rd/Ollivers Rd Transect

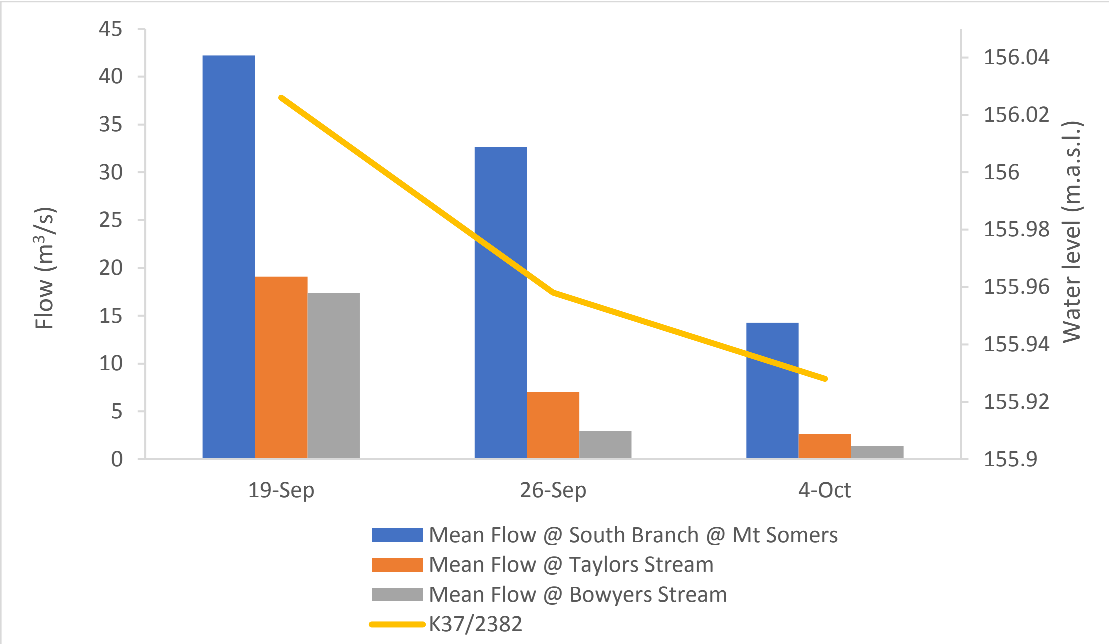

Figure B.1. Comparison of water levels in well K37/2382 and river flow levels at three recorder sites.

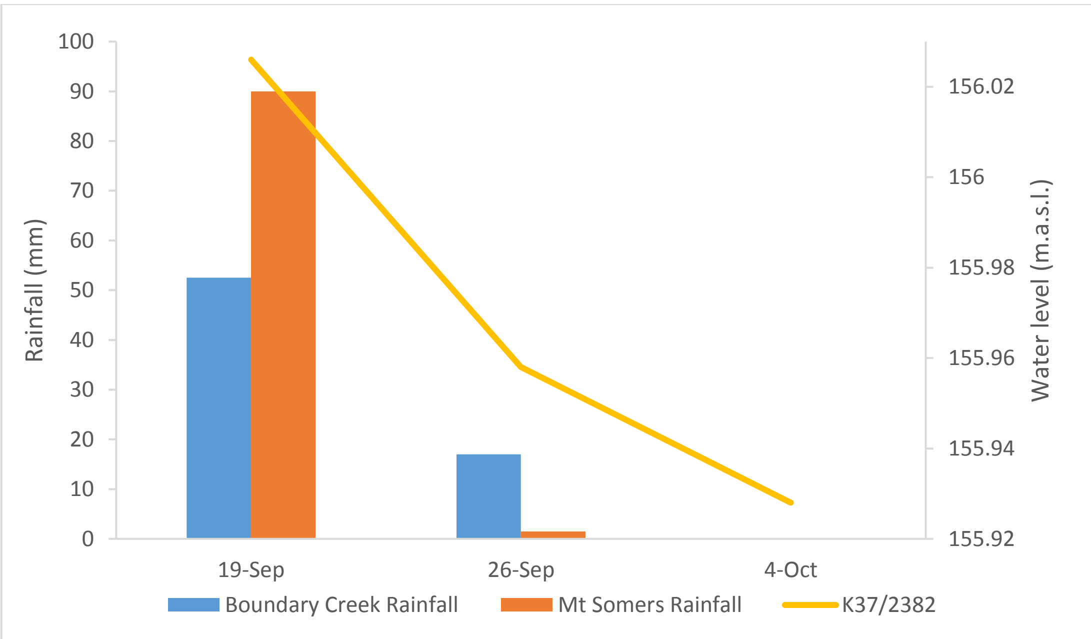

Figure B.2. Comparison of water levels in well K37/2382 and rainfall at two recorder sites.

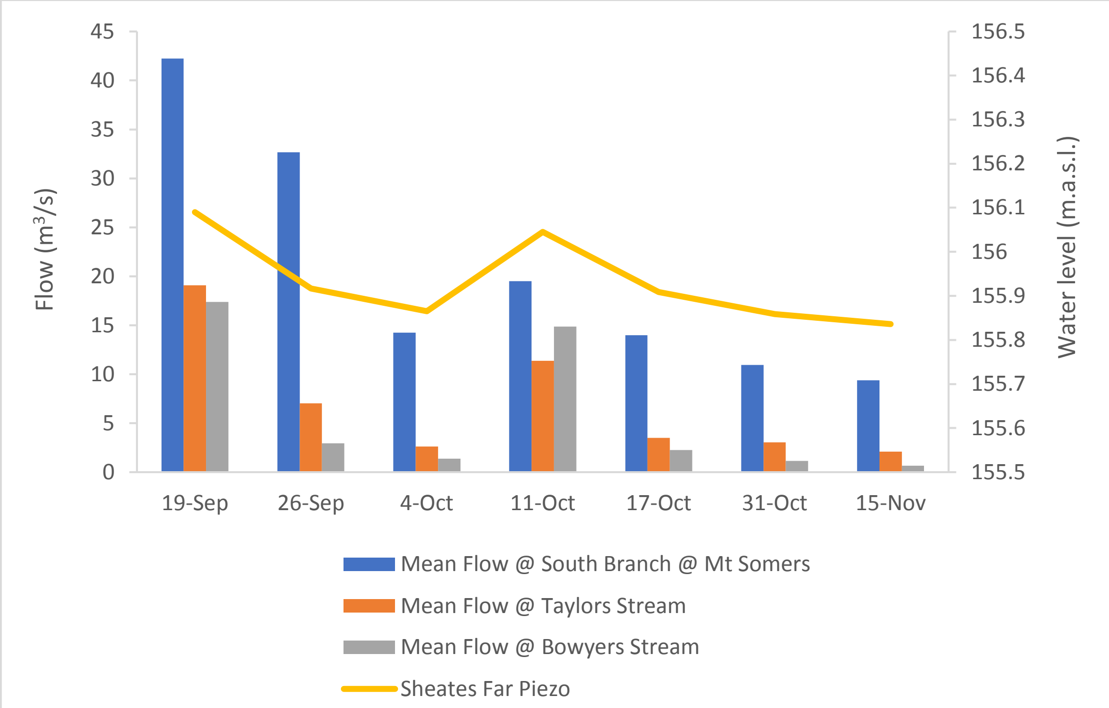

Figure B.3. Comparison of water levels in the Sheates Rd far mini-piezometer and river flow levels at three recorder sites.

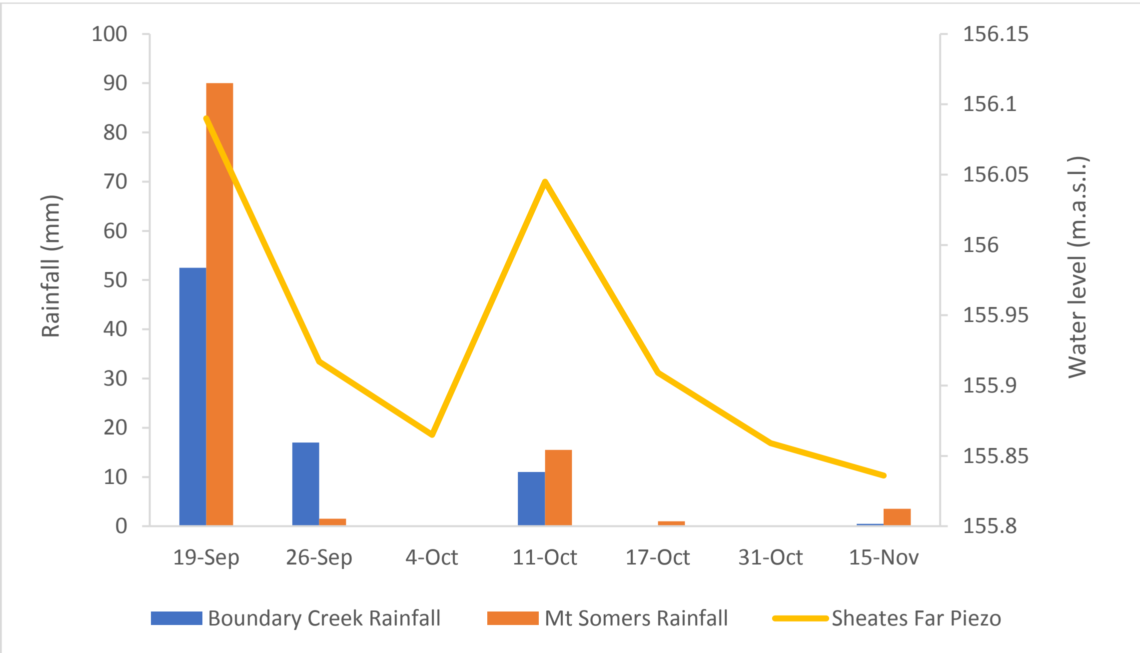

Figure B.4. Comparison of water levels in Sheates Rd far mini-piezometer and rainfall at two recorder sites.

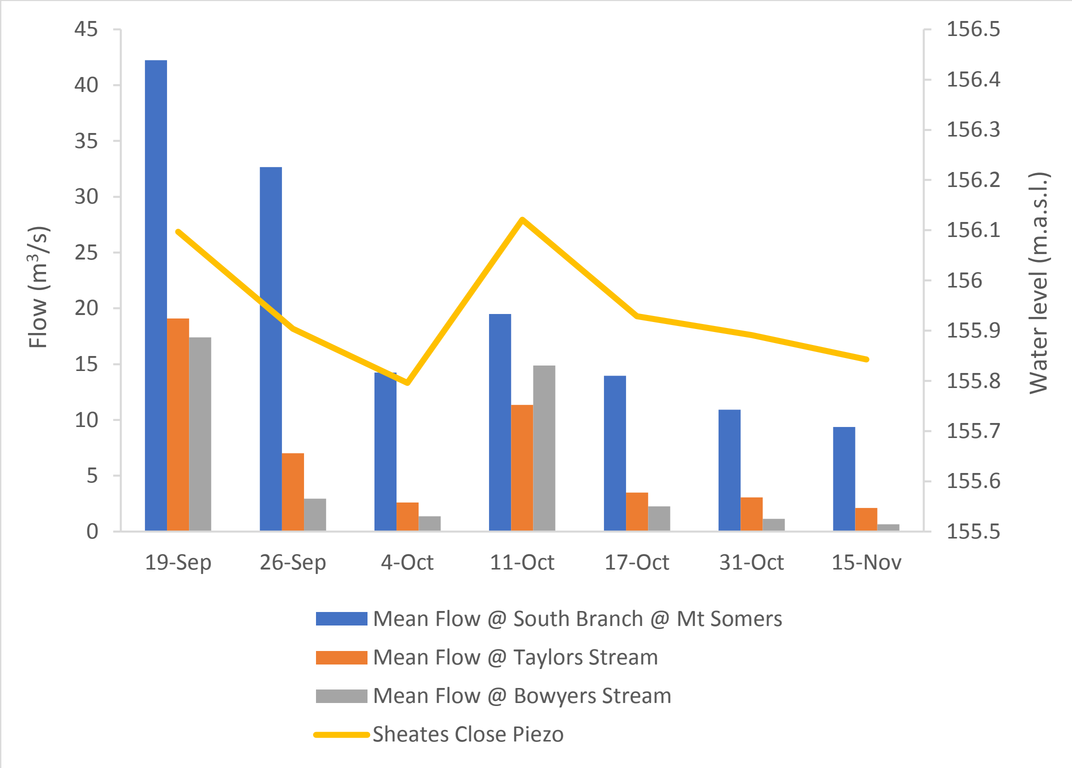

Figure B.5. Comparison of water levels in the Sheates Rd close mini-piezometer and river flow levels at three recorder sites.

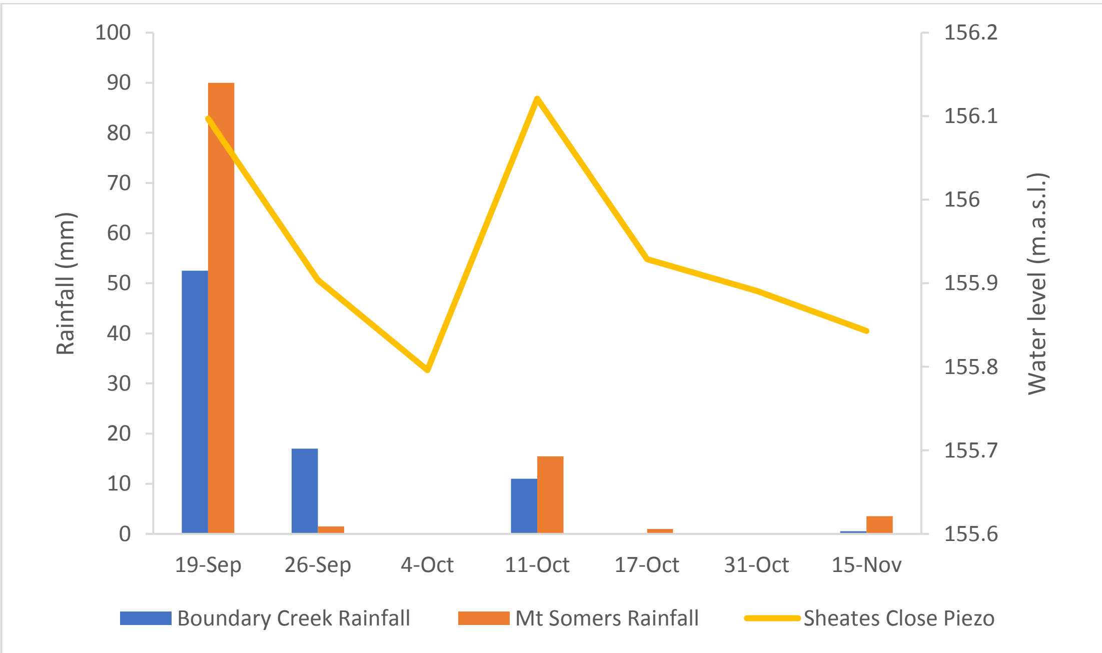

Figure B.6. Comparison of water levels in Sheates Rd close mini-piezometer and rainfall at two recorder sites.

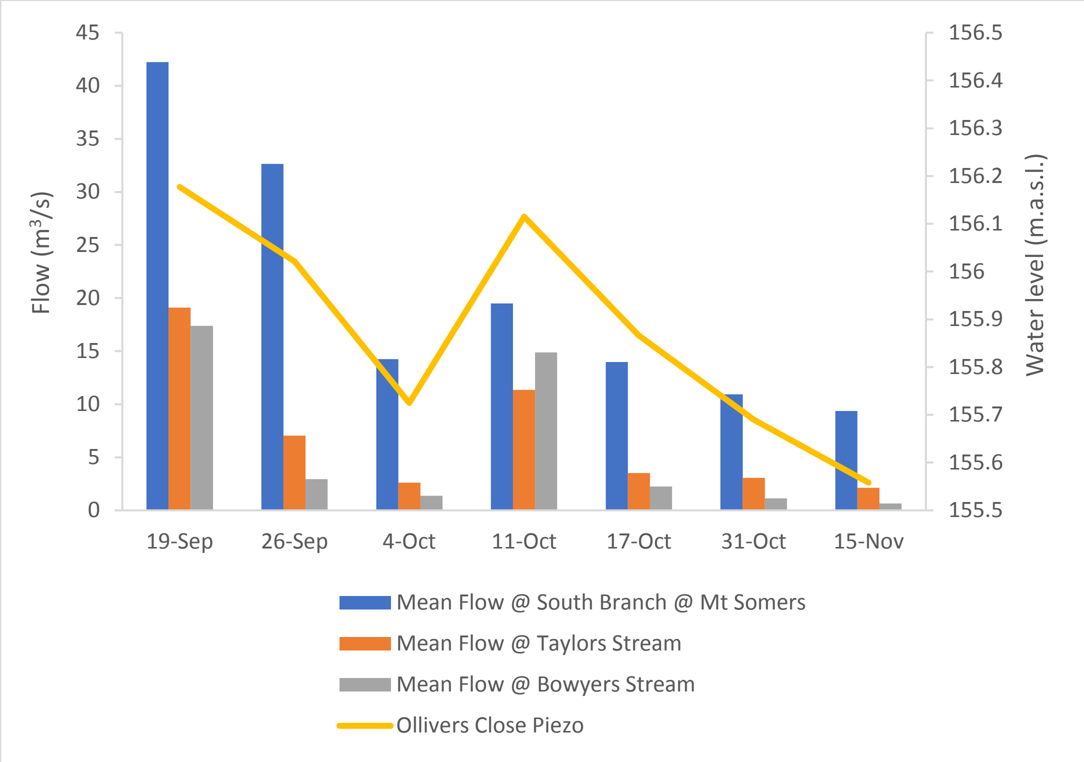

Figure B.7. Comparison of water levels in the Ollivers Rd close mini-piezometer and river flow levels at three recorder sites.

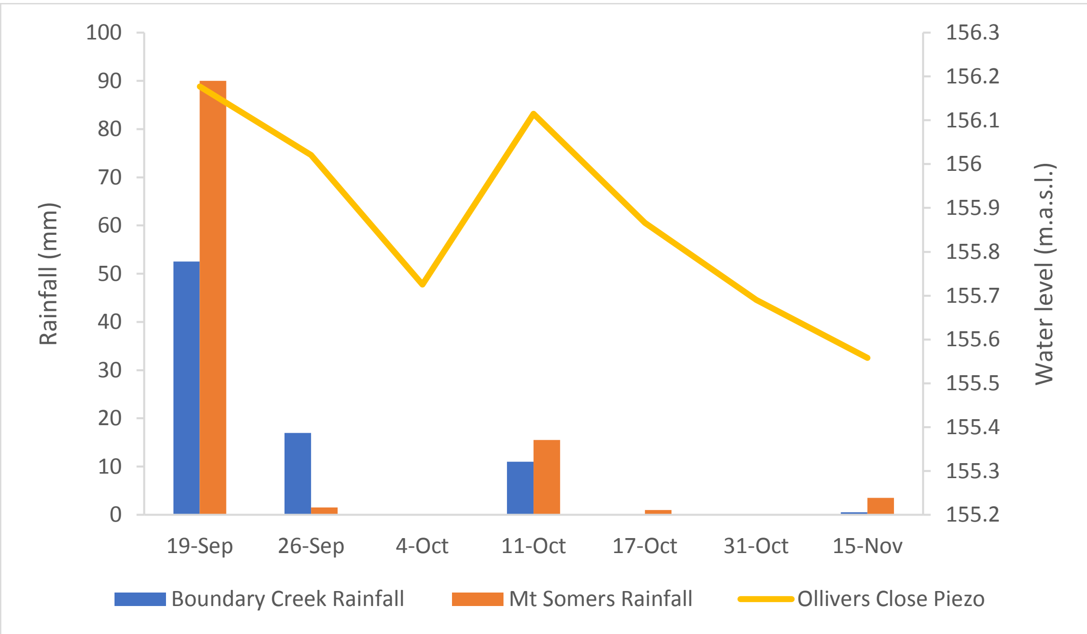

Figure B.8. Comparison of water levels in Ollivers Rd close mini-piezometer and rainfall at two recorder sites.

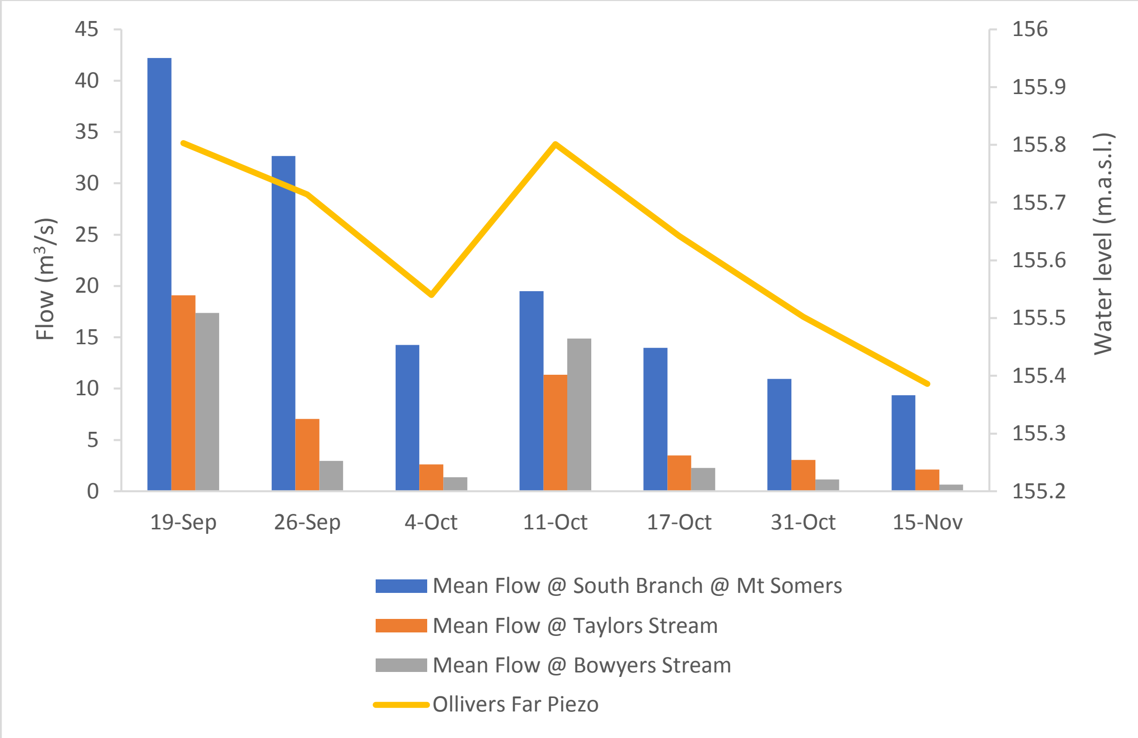

Figure B.9. Comparison of water levels in the Ollivers Rd far mini-piezometer and river flow levels at three recorder sites.

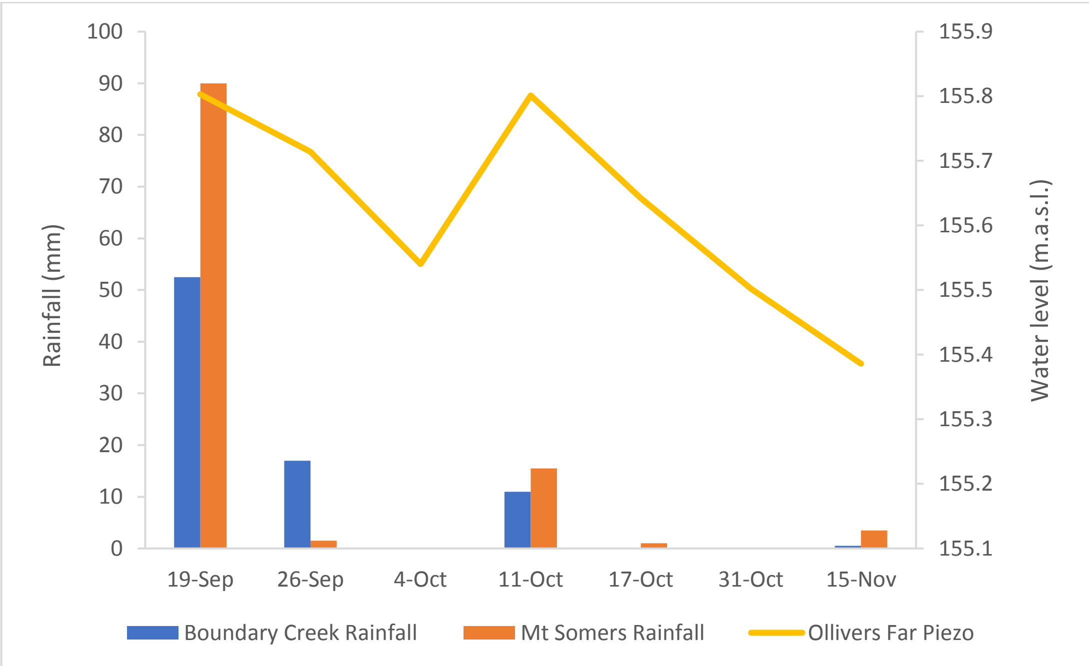

Figure B.10. Comparison of water levels in Ollivers Rd far mini-piezometer and rainfall at two recorder sites.

Mill Rd/Blacks Rd Transect

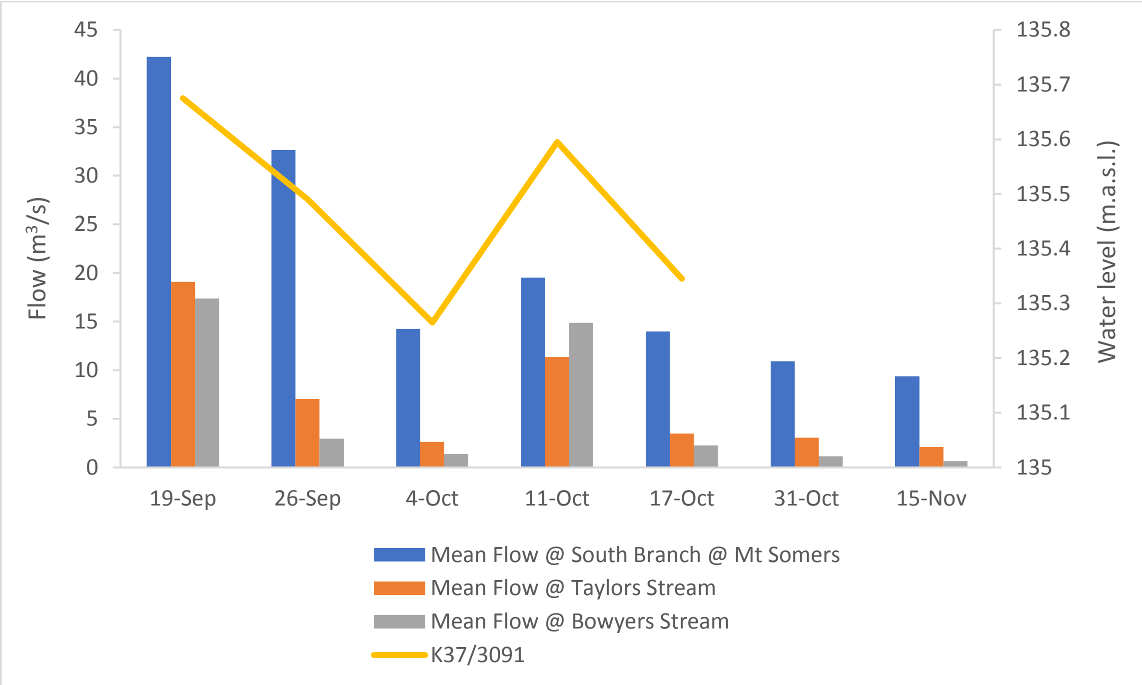

Figure B.11. Comparison of water levels in well K37/3091 and river flow levels at three recorder sites.

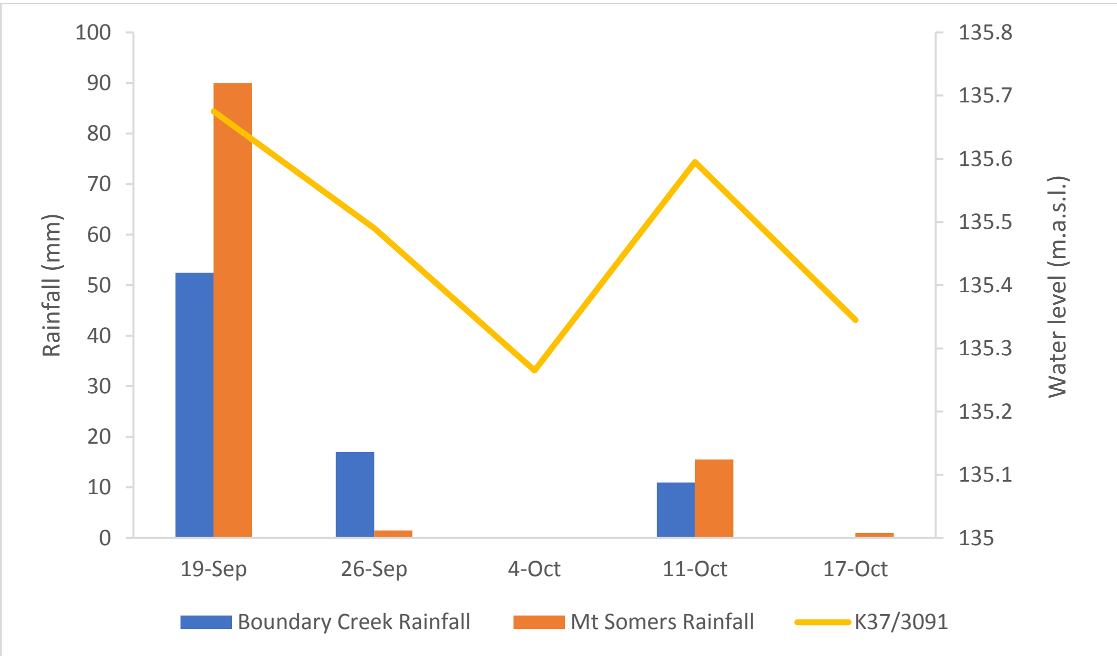

Figure B.12. Comparison of water levels in well K37/3091 and rainfall at two recorder sites.

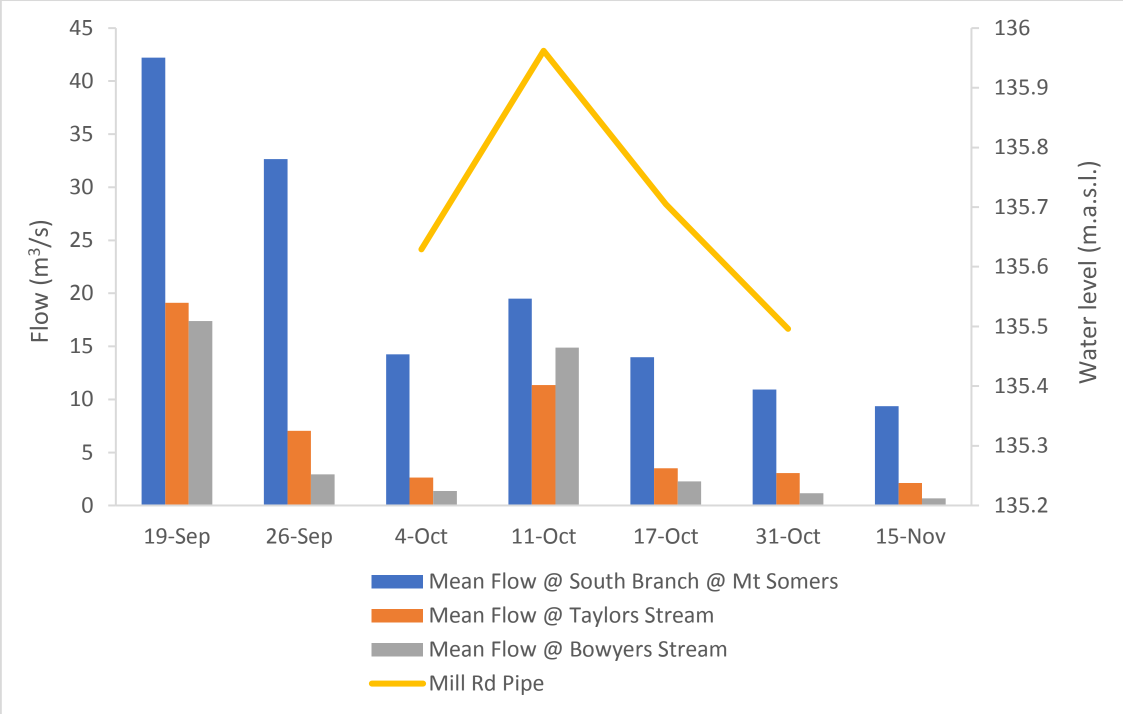

Figure B.13. Comparison of water levels in the Mill Rd Pipe and river flow levels at three recorder sites.

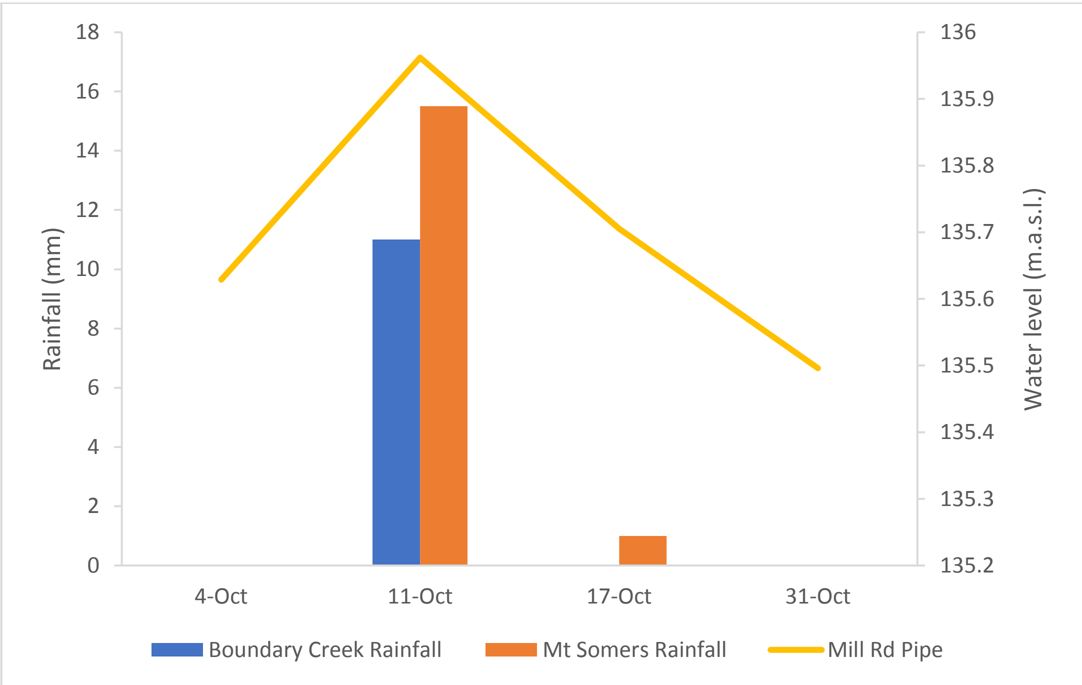

Figure B.14. Comparison of water levels in the Mill Rd Pipe and rainfall at two recorder sites.

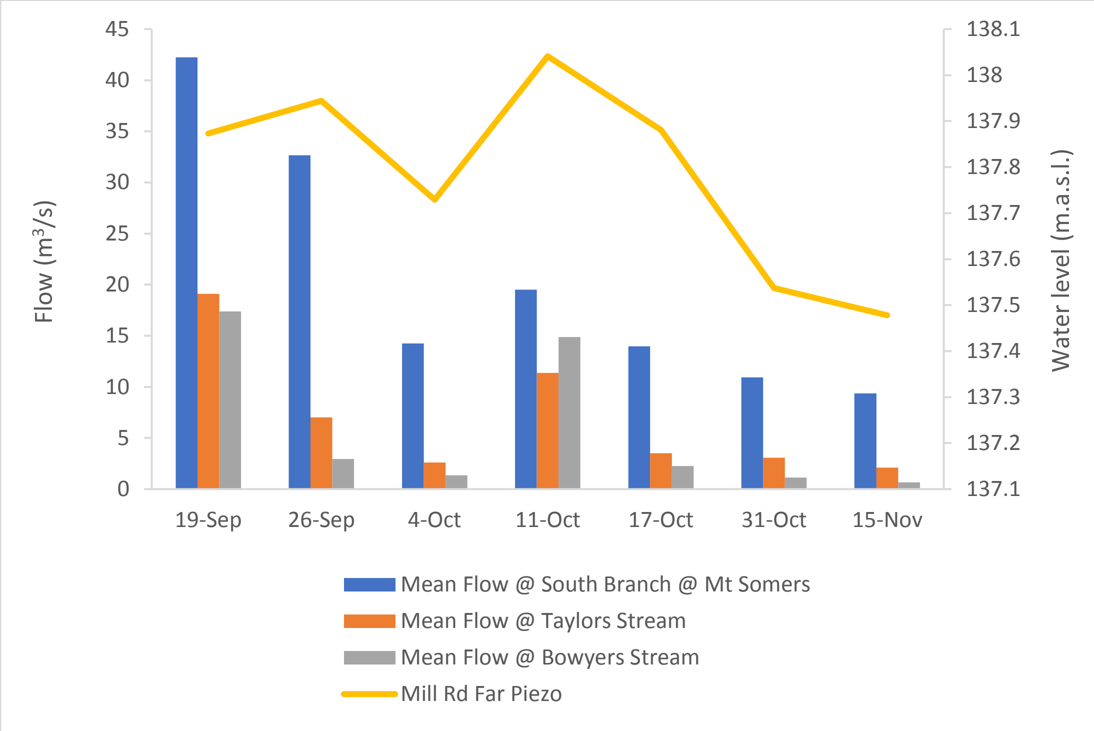

Figure B.15. Comparison of water levels in the Mill Rd far mini-piezometer and river flow levels at three recorder sites.

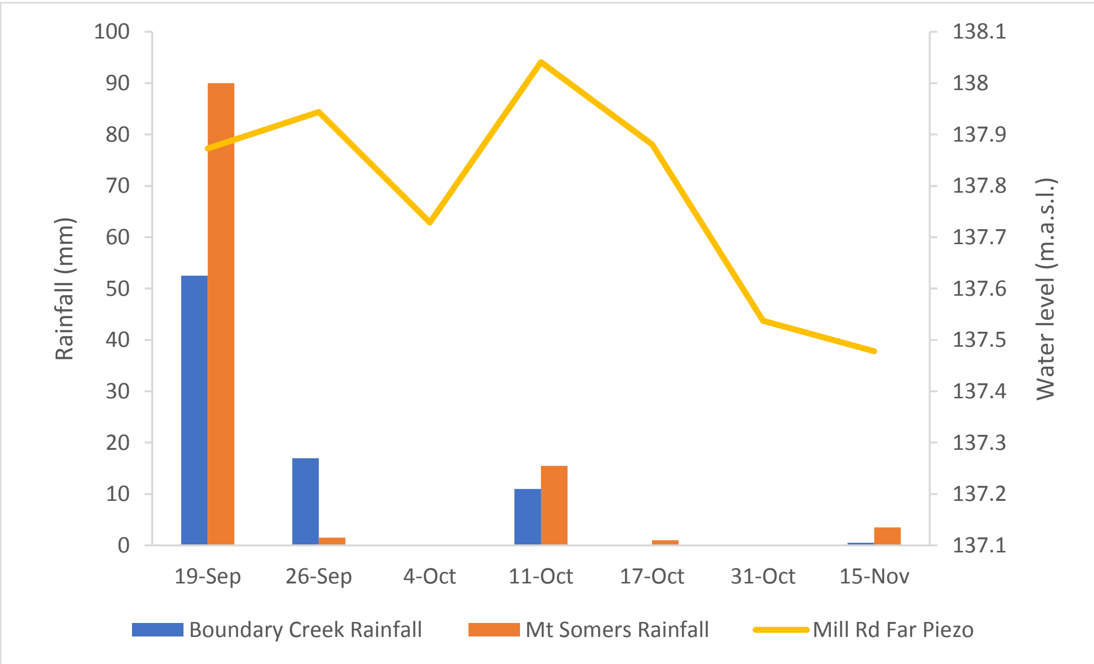

Figure B.16. Comparison of water levels in the Mill Rd far mini-piezometer and rainfall at two recorder sites.

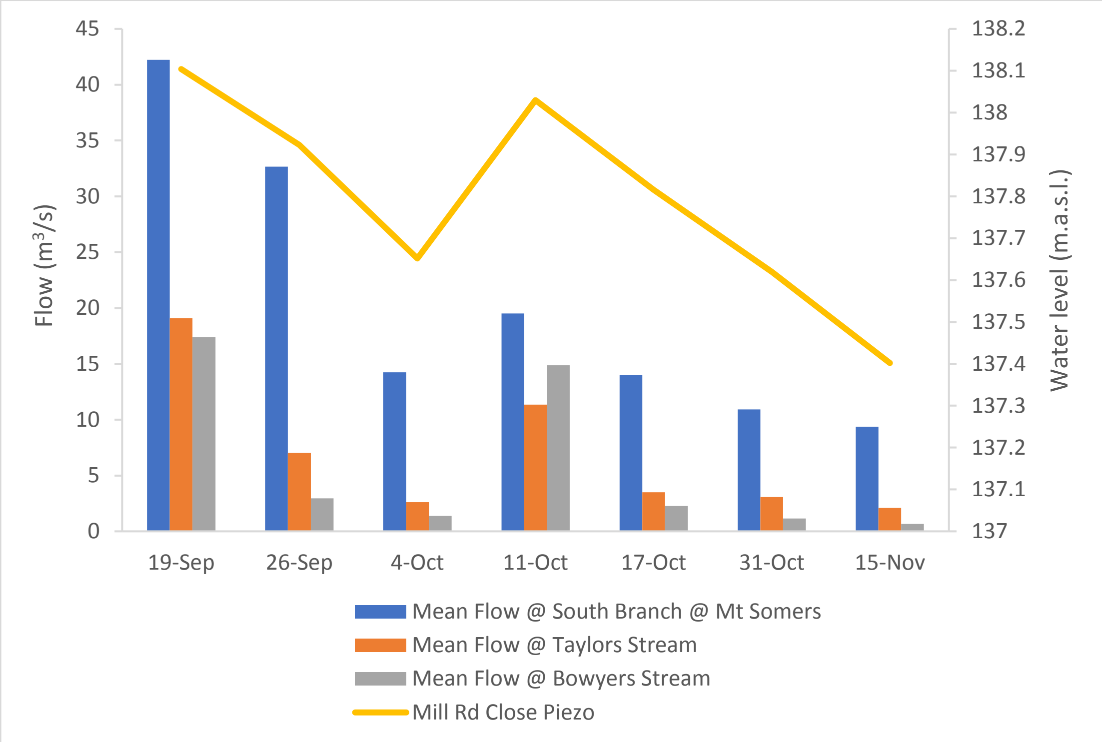

Figure B.17. Comparison of water levels in the Mill Rd close mini-piezometer and river flow levels at three recorder sites.

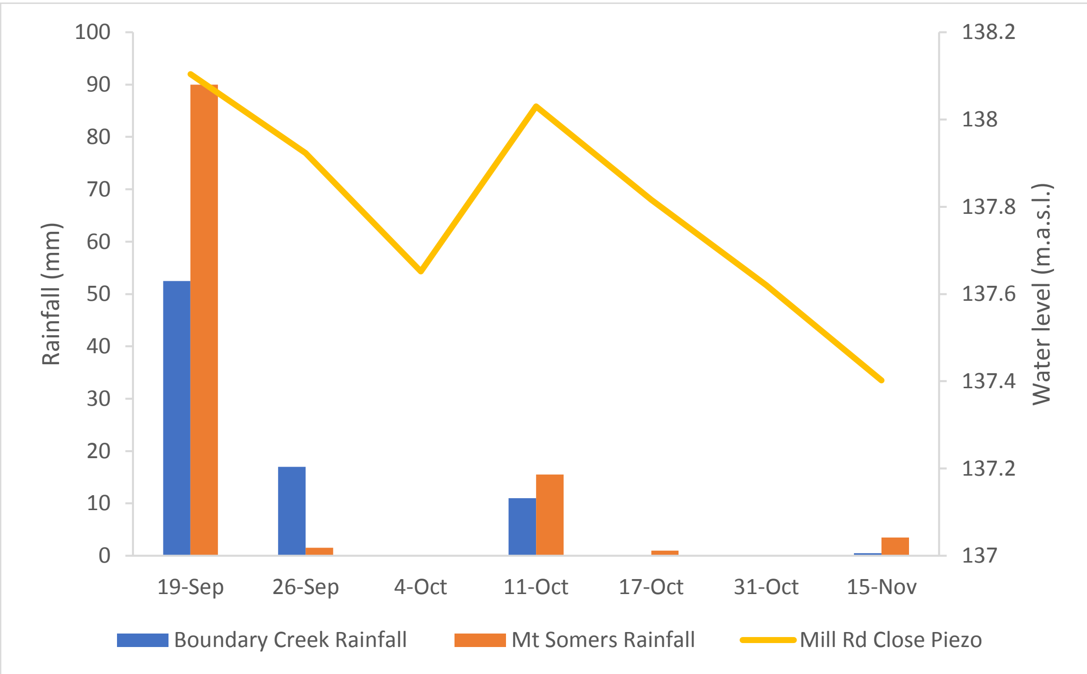

Figure B.18. Comparison of water levels in the Mill Rd close mini-piezometer and rainfall at two recorder sites.

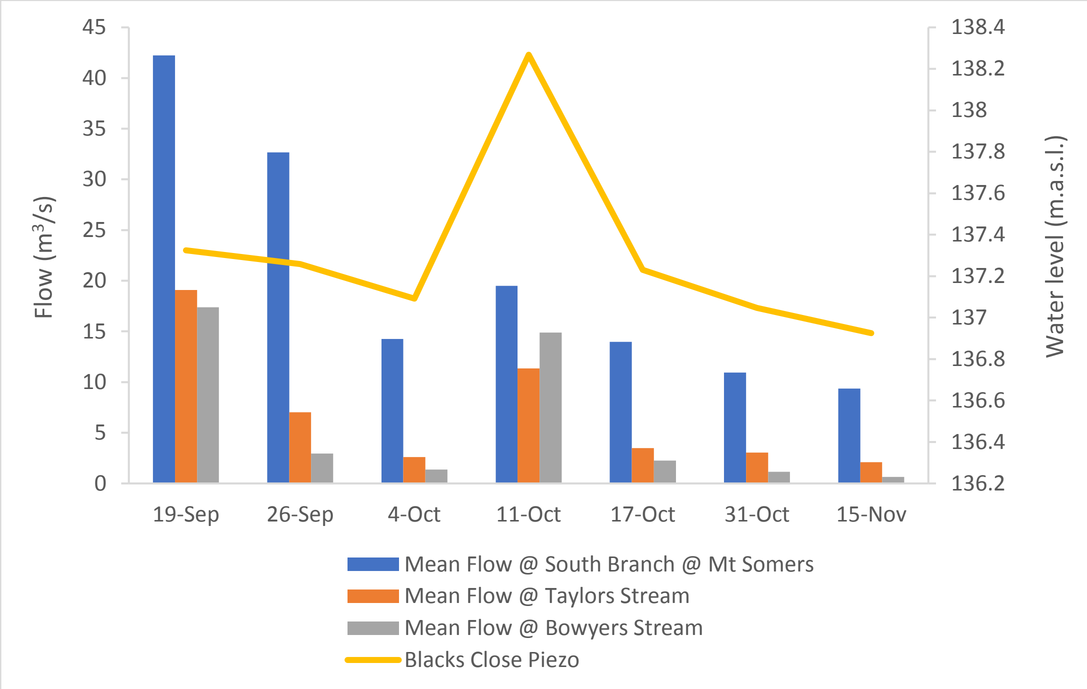

Figure B.19. Comparison of water levels in the Blacks Rd close mini-piezometer and river flow levels at three recorder sites.

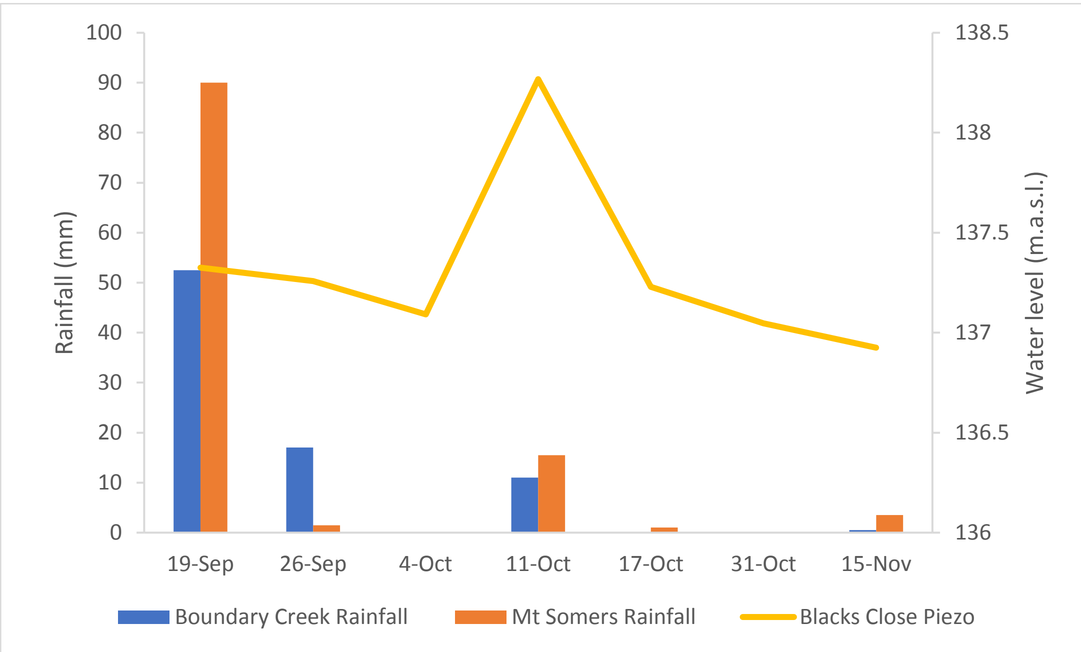

Figure B.20. Comparison of water levels in the Blacks Rd close mini-piezometer and rainfall at two recorder sites.

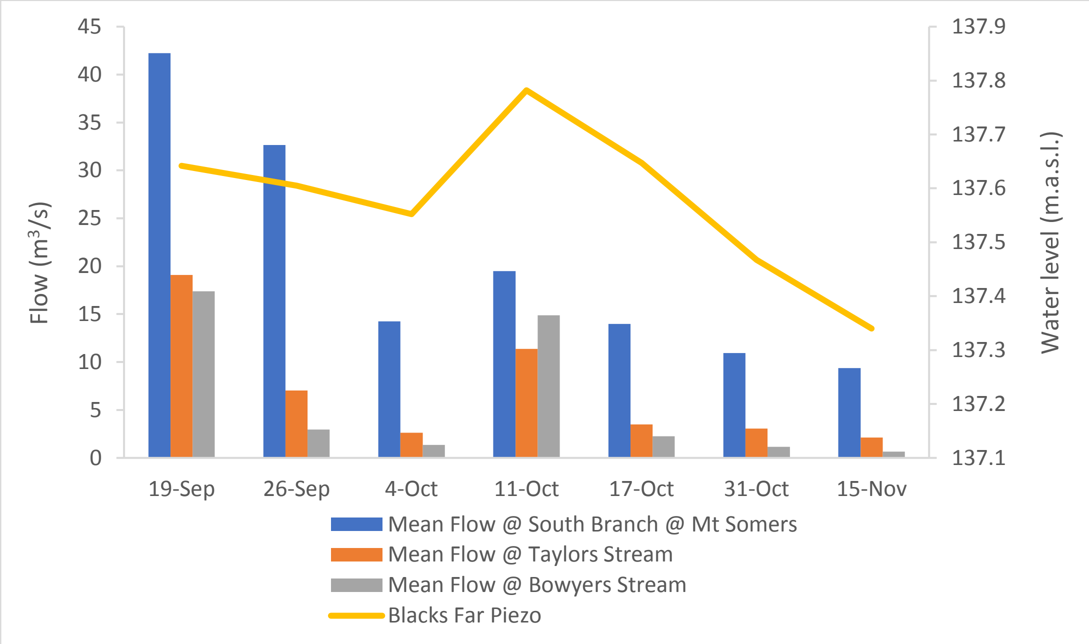

Figure B.21. Comparison of water levels in the Blacks Rd far mini-piezometer and river flow levels at three recorder sites.

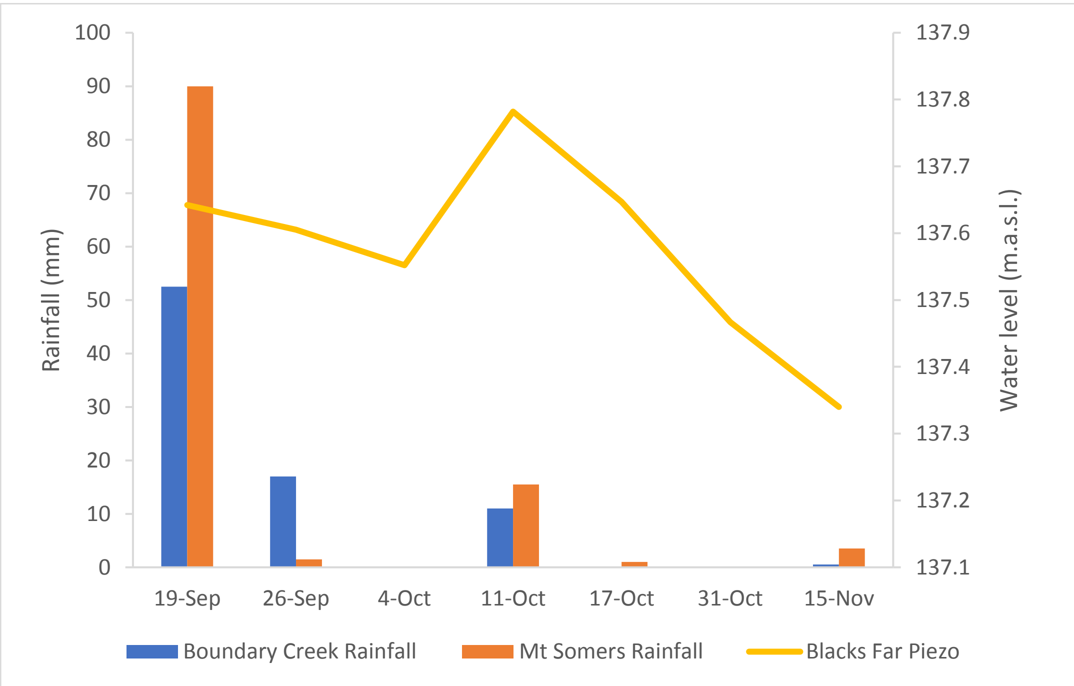

Figure B.22. Comparison of water levels in the Blacks Rd far mini-piezometer and rainfall at two recorder sites.

Appendix C. Flow levels at upstream recorder sites during temperature probe sampling runs

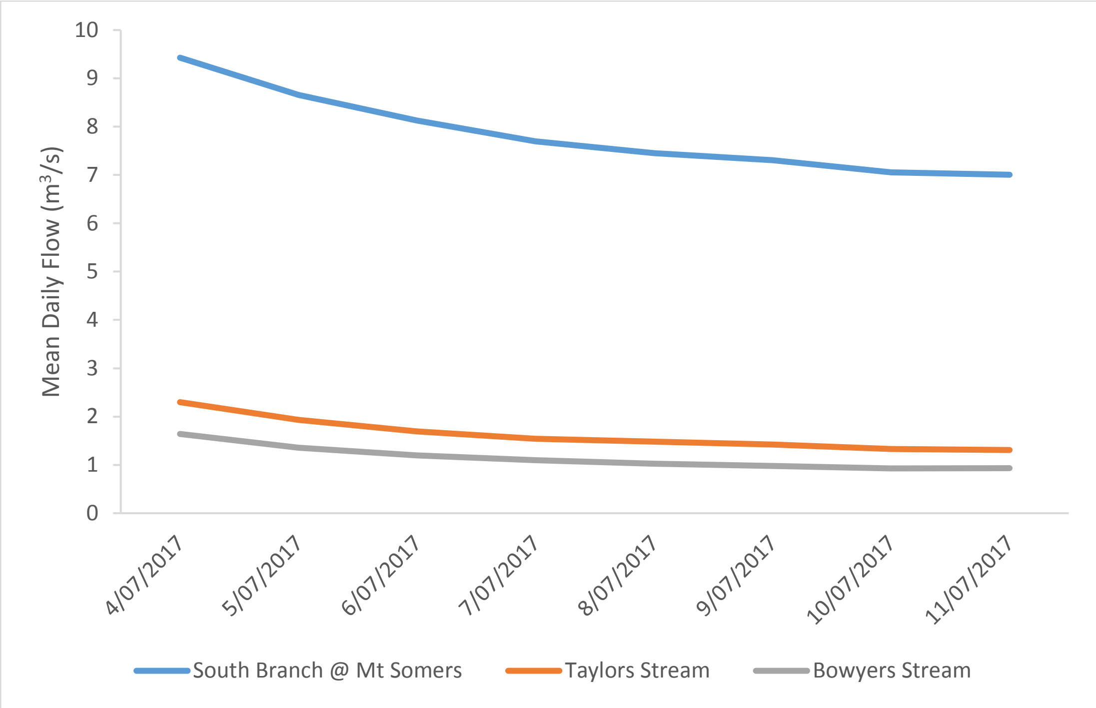

Figure C.1. Mean daily flow at three upstream river recorder sites during 4-11 July 2017.

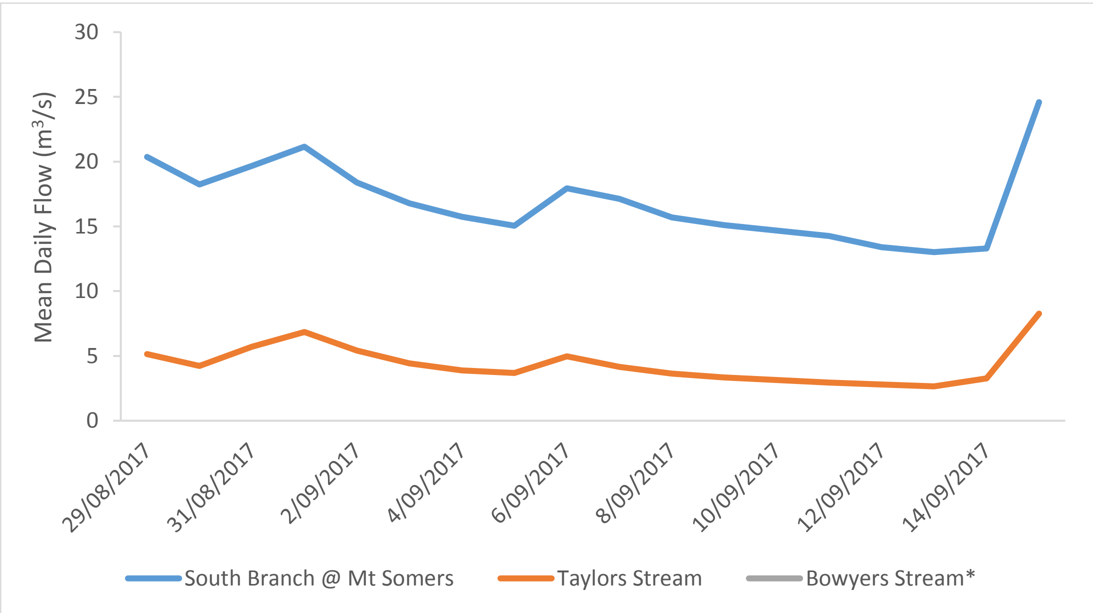

Figure C.2. Mean daily flow at three upstream river recorder sites during 29 August-15 September 2017. *There was no data recorded during the period on Bowyers Stream.

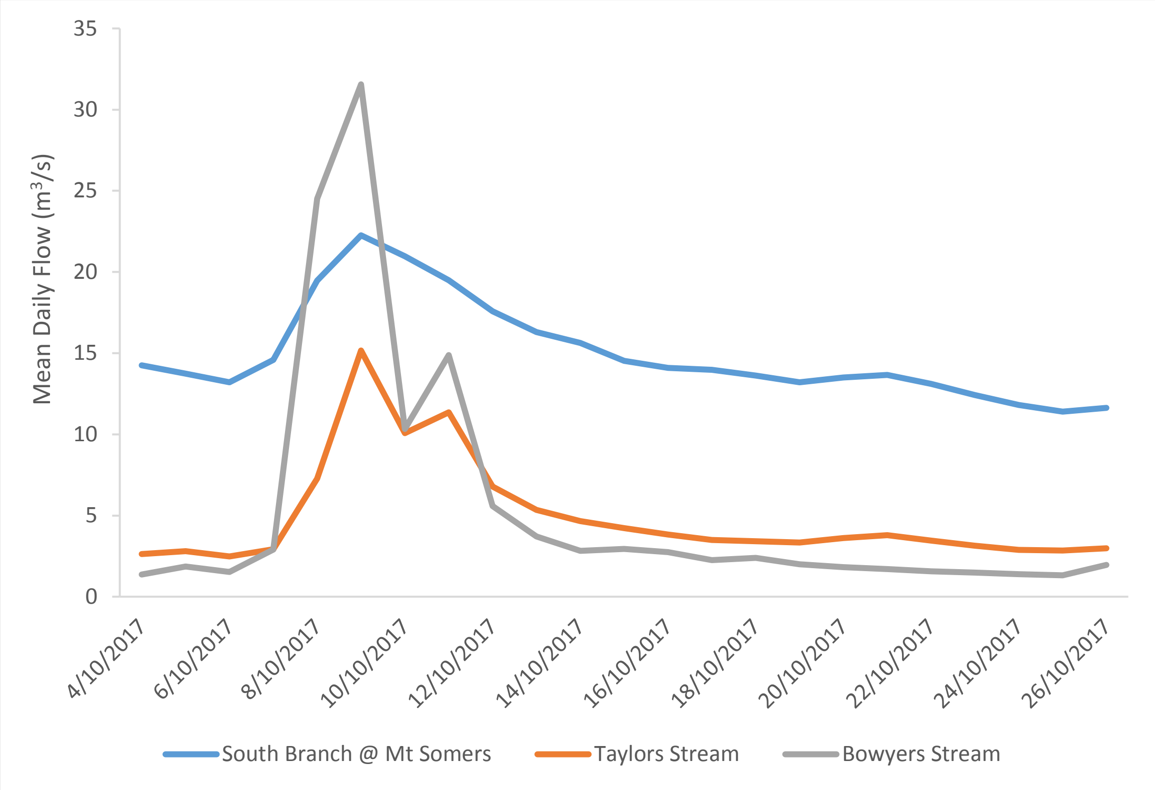

Figure C.3. Mean daily flow at three upstream river recorder sites during 4-26 October 2017.

Appendix D. Landowner results

As discussed in section 4.7, the private landowners who granted access to their land and groundwater wells for this study have been presented with the general findings of this study and the specific results for sampling on their properties. All landowners were given the following document that summarised the purpose of the study, work carried out and overall findings:

Results from Hakatere/Ashburton River Investigation

Katie Coluccio, Masters Student, Waterways Centre for Freshwater Management, University of Canterbury, Christchurch

Study Purpose: To determine ways to better measure groundwater and surface water exchange in braided rivers using the South Branch of the Ashburton River as a study site.

Work Carried Out: The majority of field work was carried out from July-November 2017 at two adjacent road crossings (Sheates Rd/Ollivers Rd & Mill Rd/Blacks Rd). Work included:

- Measuring water levels in mini-piezometers (small pipes installed in river and on banks) and groundwater wells.
- Chemically analysing water in mini-piezometers and groundwater wells.
- Measuring temperature at different depths in streambed.

General Findings:

- Results showed some areas of the study sites where groundwater is seeping into the streambed.
- Other areas appear to be losing river water to groundwater.
- There were relatively higher concentrations of conductivity and nitrate-nitrogen inland and they decreased towards the river. This may indicate river water is diluting shallow groundwater very close to the river.

Results from your property are on page 2.

Many thanks for your assistance with this research – it would not have been possible without the help of local landowners.

If there are any questions, please do not hesitate to contact me.

Table D.1. shows an example of results provided to a landowner for sampling on their property:

Table D.1. Results from Well ID K37/3091

Well ID	**Date**	**Water Level Below Ground (m)**	**Temperature (°C)**	**pH**	**Conductivity (µS/cm)**	**Nitrate-Nitrogen Average (mg/L)**	**Nitrate-Nitrogen Minimum (mg/L)**	**Nitrate-Nitrogen Maximum (mg/L)**
K37/3091	19-Sep-17	0.511	*	*	*	*	*	*
K37/3091	27-Sep-17	0.797	10.0	6.57	422.7	18.3	15.9	21.5
K37/3091	4-Oct-17	0.921	*	*	*	*	*	*
K37/3091	11-Oct-17	0.591	*	6.85	425.8	16.1	14.3	17.1
K37/3091	18-Oct-17	0.841	10.3	6.87	430.0	10.1	9.0	11.6
Median values		**0.797**	**10.15**	**6.85**	**425.8**	**15.9**		

***** Not measured

NZ Drinking Water Standards:

Nitrate-Nitrogen: 11.3 mg/L (maximum acceptable value)

pH: 7.0-8.5 (desired range)

Guidelines for Aquatic Life (in rivers):

Nitrate-Nitrogen:

- 6.9 mg/L (maximum level allowed by the National Policy Statement for Freshwater 2014)
- 1.0 mg/L (toxic to the most sensitive species)

Appendix E. Bird survey

Despite the intensive land use near the study sites in this thesis work, there are a variety native and exotic bird species found in this area. The following is a list of all bird species found at the study sites during the course of this study:

- Spur-winged plover*
- Black-billed gull (*tarāpuka*)*
- European goldfinch
- European greenfinch
- Welcome swallow (*warou*)*
- Paradise shelduck (*pūtangitangi*)*
- Australian magpie
- House sparrow (*tiu*)
- Eurasian skylark (*kaireka*)
- Eurasian blackbird
- Song thrush
- Mallard
- Silvereye (*tauhou*)*
- Black-fronted tern (*tarapirohe*)*
- South Island pied oystercatcher (*tōrea*)*
- Common pheasant
- Mute swan
- Pied stilt (*poaka*)*
- Yellowhammer
- Swamp harrier (*kāhu*)*
- Rock pigeon
- Southern black-backed gull (*karoro*)*
- Pūkeko*
- Buff weka*
- New Zealand fantail (*pīwakawaka*)*
- Cape Barren goose

- Wild turkey
- Peacock

* Indicates a New Zealand native